EDDY CURRENT CALCULATIONS FOR A 1.495 GHz INJECTION-LOCKED MAGNETRON*

S. A. Kahn†, A. Dudas, R. P. Johnson, M. Neubauer, Muons, Inc., Batavia, IL., USA
H. Wang, Jefferson Lab., Newport News, VA, USA

Abstract

An injection-locked amplitude modulated magnetron is being developed as a reliable, efficient RF source that could replace klystrons used in particle accelerators. The magnetron amplitude is modulated using a trim magnetic coil to alter the magnetic field in conjunction with the anode voltage to maintain the SRF cavity voltage while the cavity is experiencing microphonics and changing beam loading. Microphonic noise can have frequency modes in the range 10-50 Hz. Eddy currents will be induced in the copper anode of the magnetron that will buck the field in the interaction region from the trim coil. This paper will describe the magnetic circuit of the proposed magnetron as well as the calculation and handling of the Eddy currents on the magnetic field.

INTRODUCTION

A magnetron with injection locking and amplitude modulation is being proposed as an efficient alternative to klystrons. The project plans to build and test a prototype 1497 MHz magnetron that could be used as an RF source for JLab. Using an injection phase-locked magnetron as an alternate RF source is described in Ref. [1]. Amplitude modulation is planned to control microphonics in the superconducting RF cavities. The current in the magnetron interaction region is modulated by varying the magnetic field over the electron cloud. The magnet system consists of a DC solenoid that provides the nominal field over the interaction region. An additional coil surrounds the anode which can provide a variable ±10% field to modulate the current. The magnet system is described in the next section. The JLab superconducting cavities have microphoninc noise modes in the frequency range 10-50 Hz [2].

MAGNET SYSTEM

Figure 1 shows a diagram of the magnetron which illustrates the magnet configuration. The larger outer solenoid coils provide 0.25 T field. A trim coil is present surrounding the anode to provide an additional variable field that can be used to modify the field in the interaction region. Surrounding the coils is a steel magnetic circuit to conduct the flux to the magnetron interaction region. This configuration provides a uniform magnet field over the interaction region. Table 1 shows parameters describing the trim coil. The decay constant associated with the coil

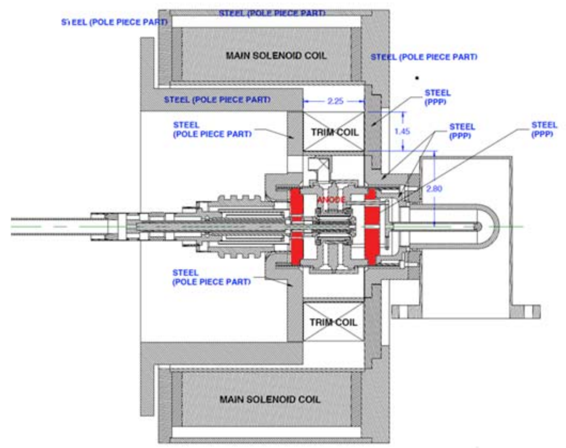


Figure 1: Diagram of magnetron showing the magnet configuration.

Table 1: Trim Coil Parameters

Parameter	Value
Maximum Field	0.025 T
Number of turns	248
Current per turn	5 A
Inductance	0.028392 h
Coil Resistance	0.279 Ω
Time Decay Constant	100 ms
Cross Section Area	21.05 cm^2

coil inductance is 100 ms. This number is independent of the number of turns as long as the coil cross section is fixed. The decay constant may be too long to react to very short time spikes. The decay constant can be further reduced with an external resistance in series with the trim coil, however that resistance must be compatible with the 5 A current and may limited by the power supply.

EDDY CURRENT SHIELDING

The time varying currents in the trim coil will induce transient currents in the magnetron anode which is made of copper. The Eddy current in the anode will produce a field in the interaction region that opposes the field from the trim coil. We used the Opera 2D finite element simulation code [3] to model the magnetic geometry configuration of the magnetron. The anode in the R-Z is represented by a cylinder with radial thickness corresponding to the part of the anode that would allow the current to circulate the full 360° since that is the region that contributes significantly to the Eddy currents. The analysis uses a sinusoidal drive current in the trim coil with frequen-

* Work supported by U.S. D.O.E. SBIR grant DE-SC0013203
† email address: kahn@muonsinc.com

cies: 10.5 Hz, 23.5 Hz, 41.5 Hz and 75 Hz. These frequencies correspond to cavity microphonic noise modes seen in Ref. [2]. Figure 2 shows the Eddy currents induced in the anode from a 10.5 Hz trim coil current. The trim current is shown as dashed and the current induced in the anode is shown as solid. The Eddy currents have the opposite direction to the trim current which reduces the field in the interaction region. Figure 3 shows the ratio of the amplitude of current in the copper anode to the current in the trim coil at different steady state frequencies. As expected the larger the frequency the larger the Eddy current.

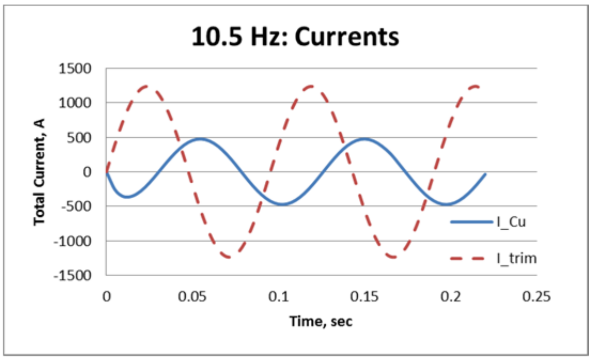


Figure 2: Eddy currents induced in the anode are shown in blue for a 10.5 Hz sinusoidal trim current which is shown in red.

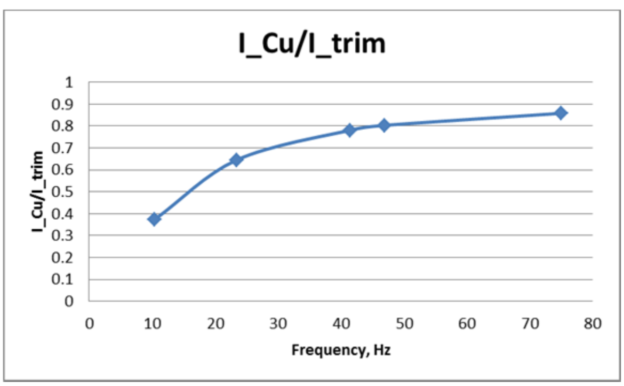
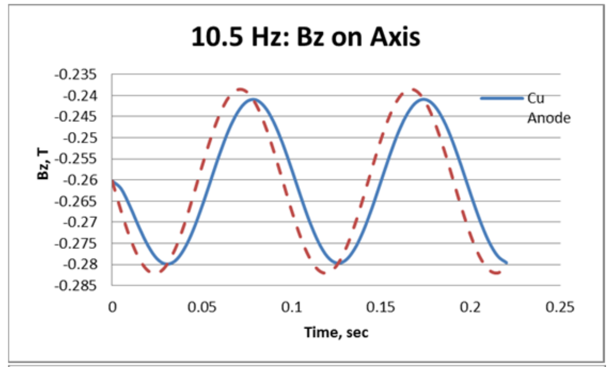


Figure 3: Ratio of Eddy Current in the copper anode to the trim coil current as a function of frequency.

The effect of the Eddy currents on the field in the interaction region can be seen in Figure 4 for 10.5 Hz and 41.5 Hz. The field with (without) the anode present is shown by a solid (dashed) curve. At 10.5 Hz the Eddy current has a minimal effect on the field in the interaction region. At 41.5 Hz the field in the interaction region has been reduced to about half. Figure 5 shows the ratio of the field with the Eddy currents in the anode to the field without Eddy currents. As the frequency is increased the field in the interaction field is reduced significantly. To be effective the current in the trim coil will have to be increased to account for the Eddy currents. This will put a limit on the noise frequency that can be compensated.



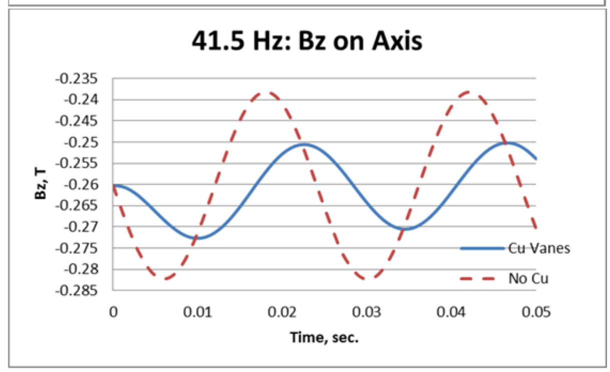


Figure 4: Field inside the interaction region for 10.5 and 41.5 Hz. The solid (dashed) curves show the field with (without) anode Eddy currents present.

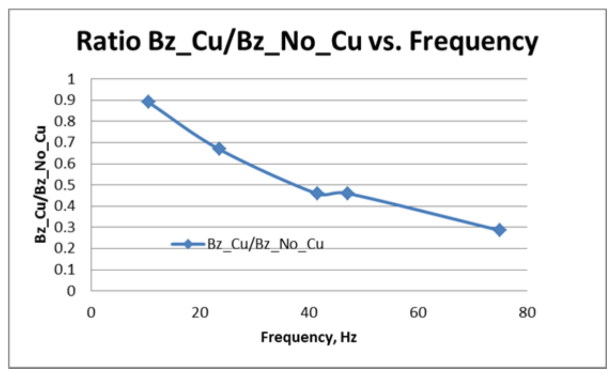


Figure 5: The ratio of the field with the anode Eddy currents to the field without the Eddy currents.

REDUCING THE EDDY CURRENTS

Large Eddy currents are induced in the anode because the anode surrounds a large time varying magnetic flux. If the anode can be segmented azimuthally and the segments are isolated from each other by insulation so that the current does not travel around the full outer ring the transient flux is reduced. If the anode is segmented along radial mid-plane through each of the vanes and reassembled (with epoxy) with the insulation between the vane halves, the π-mode symmetry of the cavity fields is preserved. Figure 6 shows contour plots of the induced Eddy current density in the anode for the case with a 47.5 Hz sinusoidal drive current in the trim coil where the trim current is near the maximum. The calculations are made in 3D using the Elektra [3] program. Figure 6a shows the induced current density for the case without any insulation in the anode. The figure shows a large induced current flowing in the outer ring since it surrounds the large magnetic flux region. Figure 6b shows the current density contour plot for the case where insulation is placed on the radial mid-plane of each vane. The current is restricted to circulate near the perimeter of each cavity section separately. The enclosed area of each section is smaller and the magnetron interaction region is not included. The Eddy currents are significantly reduced.

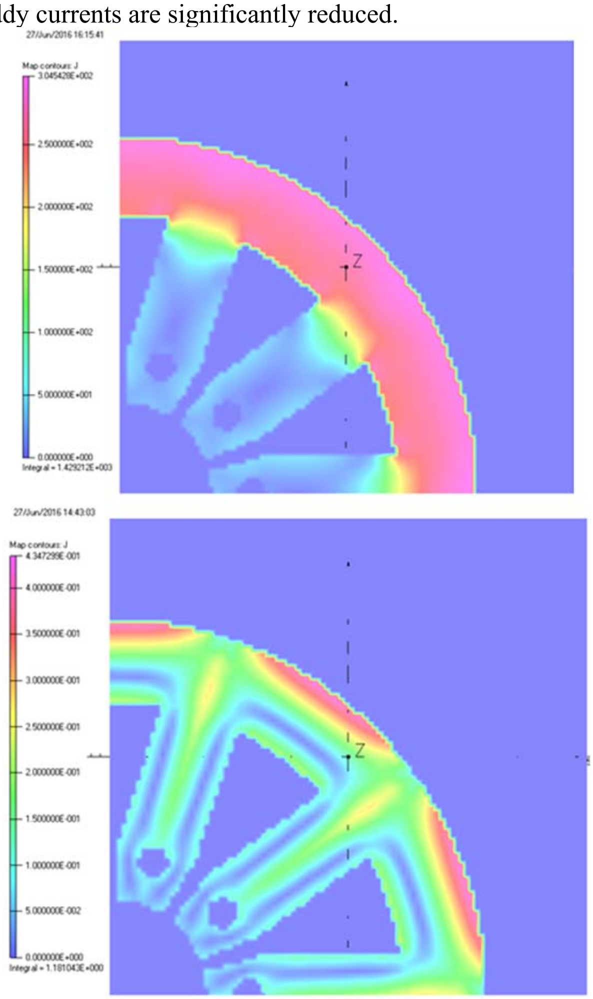


Figure 6: Contour plots of the induced Eddy current density in the anode. The upper plot (a) shows the current density without mid-vane insulation. The lower plot (b) shows the current density distribution with insulation separating the two halves of each vane along the vane radial mid-plane.

Figure 7 shows the current density normal to the radial plane midway through the cavity (half way between the adjacent vanes). The figure shows the case with (dashed) and without (solid) mid-vane insulation. For the case with insulation, some of the current is returned locally within the cavity section. The integrated current crossing the plane is 1444 A (94 A) for the case without (with) mid-vane insulation. Figure 8 shows the field in the interaction region for the cases with (solid curve) and without insulation (dashed curve) along with the case without Eddy currents (dotted curve) for comparison. For this case with 47.5 Hz drive current, the field with insulation is 80% of the field without Eddy current whereas the field without insulation is 37% of the field without Eddy currents.

We have not studied the manufacturing issues to fabricate the anode with insulation however if it were necessary to compensate for noise with a frequency greater than 50 Hz this approach could be considered.

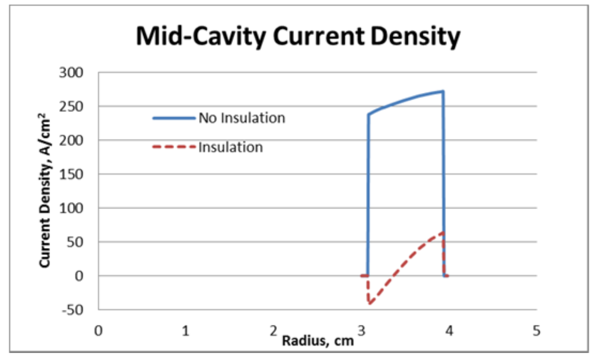


Figure 7: Current density across a radial plane through the cavity. The solid (dashed) curve shows J for the case without (with) insulation at the vane mid-plane.

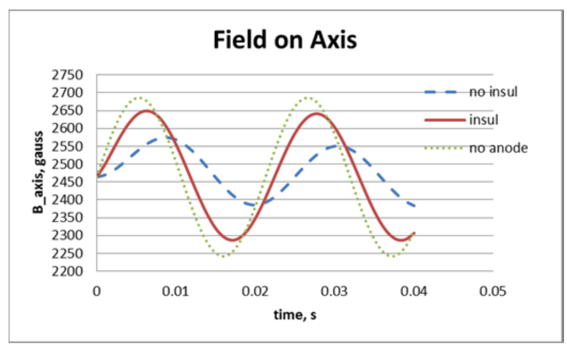


Figure 8: Field in the interaction region for the cases with insulation, no insulation and no Eddy currents for 47.5 Hz trim drive current.

CONCLUSION

We have studied using amplitude modulation with a magnetron to control microphonics from a superconducting cavity. A trim coil is used to vary the magnetic field in the magnetron as a means to provide the modulation. Eddy currents in the anode will shield trim coil current. For frequencies below 50 Hz the Eddy currents can be compensated for by increasing the trim current.

REFERENCES

[1] H. Wang *et al.*, "Simulation Study Using an Injection Phase-Locked Magnetron…", in *Proc. of IPAC2015*, p. 3544.
[2] K. Davis,"R100/C100 Cryomodule Microphonics", http://www.jlab.org/indico/event/109/session/1/contribution/material/slides/1.pdf, 2015.
[3] Vector Fields Opera Finite Element Simulation Program, Cobham Technical Services.