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

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Abstract

An injection-locked amplitude modulated magnetron is being developed as a reliable, efficient RF source that could replace klystrons used in particle accelerators. A trim magnetic coil is used to alter the magnetic field in conjunction with the anode voltage to maintain an SRF cavity voltage while the cavity is experiencing microphonics and changing beam loading. The microphonic noise modes have frequencies in the range 10-100 Hz. The changing magnetic field will induce transient eddy currents in the copper anode of the magnetron which will buck the field in the interaction region. This paper will describe the calculation and handling of the eddy currents in the magnetron.

INTRODUCTION

An injection locking magnetron with amplitude modulation is being proposed as an efficient alternative to the klystron. A prototype 1495 MHz magnetron is being built and will be tested as an RF power source that could be used for the JLab accelerator. The use of an injection phase locked magnetron as an alternate RF power source to the klystron is studied in Ref. [1]. The magnetron will be designed to compensate for microphonic noise in superconducting cavities by maintaining a constant gradient in the cavities [2]. The JLab superconducting cavities have microphonic modes in the frequency range 10-100 Hz [3]. The current in the magnetron interaction region is modulated by varying the magnetic field over that region. The magnet system consists of a DC solenoid that provides the nominal field in the interaction region. An additional coil (referred to as trim coil) surrounding the anode can provide a variable ±10% field to modulate the current [4]. The time variation of the trim coil field introduces eddy currents into the anode which is the main concern of this paper.

MAGNET SYSTEM

Figure 1 shows a diagram of the R&D version of magnetron which is currently being built. The figure shows the magnet configuration. The larger outer coil provides a 0.25 T DC field. This DC coil which exists is being used in the experimental program, however a permanent magnet would likely be used in the production version of the magnetron. The trim coil which surrounds the anode provides a tuneable field to add to the interaction region field. 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.

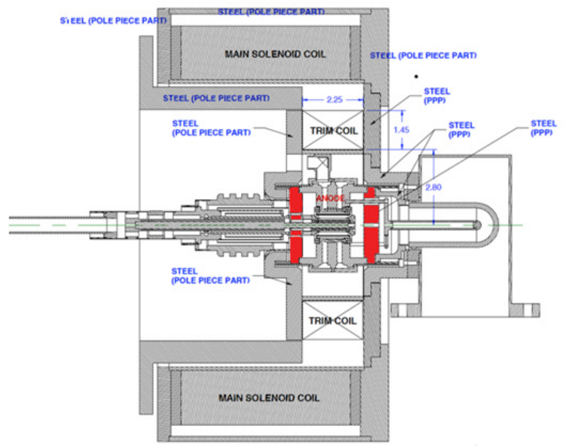

Figure 1: Diagram of the R&D magnetron showing the magnet configuration.

Table 1: Parameters Describing the Trim Coil

Parameter	Value
Maximum field	0.025 T
Current per turn	10 A
Number of turns	124
Inductance	0.007098 h
Coil resistance	0.069 Ω
Transient time constant	100 ms
Coil cross section area	21.05 cm^2

Table 1 shows the parameters describing the trim coil. The parameters show the case for 10 A per turn which would be wound with insulated 12 gauge wire. 16 gauge wire carrying 5 A could be used with twice the turns. The transient time constant associated with the magnet inductance and the coil resistance is 100 ms which is independent of the number of turns as long as the coil cross section area is fixed. This transient time is too long to react to very short time disturbances. The trim coil inductance is large because the coils are placed outside of the water cooling system for the anode. By placing the trim coil inside the cooling plumbing the transient time could be reduced by half. The transient decay time can be further reduced with an external resistance in series with the trim coil. The goal is to reduce the transient decay time to the 1 to 10 ms range.

ANODE EDDY CURRENTS

The time varying current in the trim coil will induce currents in the copper magnetron anode. The outer ring

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of the anode subtends a large fraction of the trim coil flux. These eddy currents will produce a field in the interaction region that opposes the field from the trim coils. The Opera 2D finite element program [5] was used to simulate the magnetron magnet system. The anode was represented in R-Z geometry as a simple cylinder with the radial thickness of the outer ring of the anode where most of the current will flow. The trim coil is driven with a sinusoidal current with frequencies corresponding to the cavity microphonic modes seen in Ref. [3]. Figure 2 shows the ratio of the amplitude of current induced in the copper anode to the trim coil current as a function of drive frequency. As expected the anode current increases with frequency. The effect of the eddy currents on the field in the interaction region can be seen in Fig. 3 which shows the ratio of the field with and without the anode current. The effectiveness of using the trim coil to compensate the cavity noise is reduced significantly at higher frequencies. For frequencies greater than 40 Hz the anode current would shield greater than half of the field. In order to retain the ability to correct the field with a variation of ±10% the trim coil current capacity will have to be increased. This will limit the microphonic frequency that can be compensated.

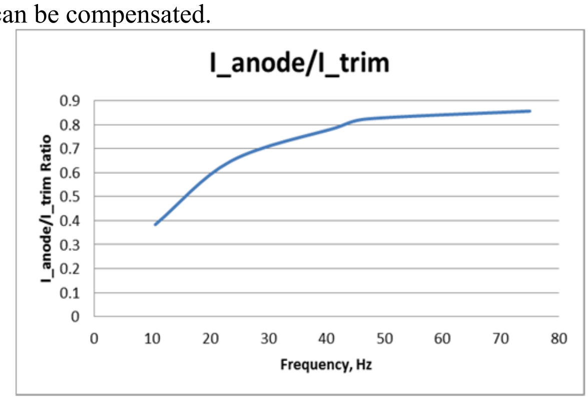

Figure 2: Ratio of eddy current in the copper anode to the trim coil current as a function of frequency.

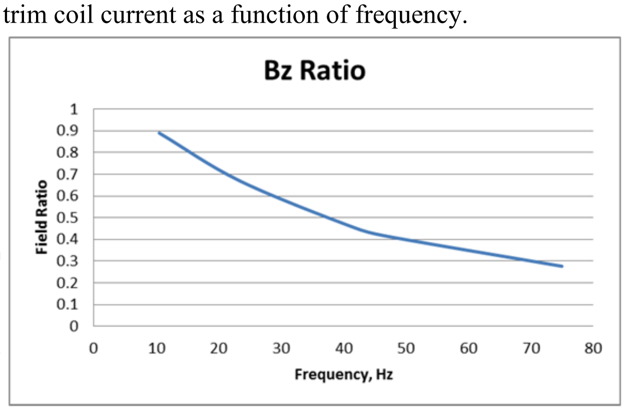

Figure 3: Ratio of interaction region field with anode eddy currents to the field without the eddy currents.

REDUCING THE EDDY CURRENTS

We have examined several approaches to reduce these anode eddy currents. These are described below.

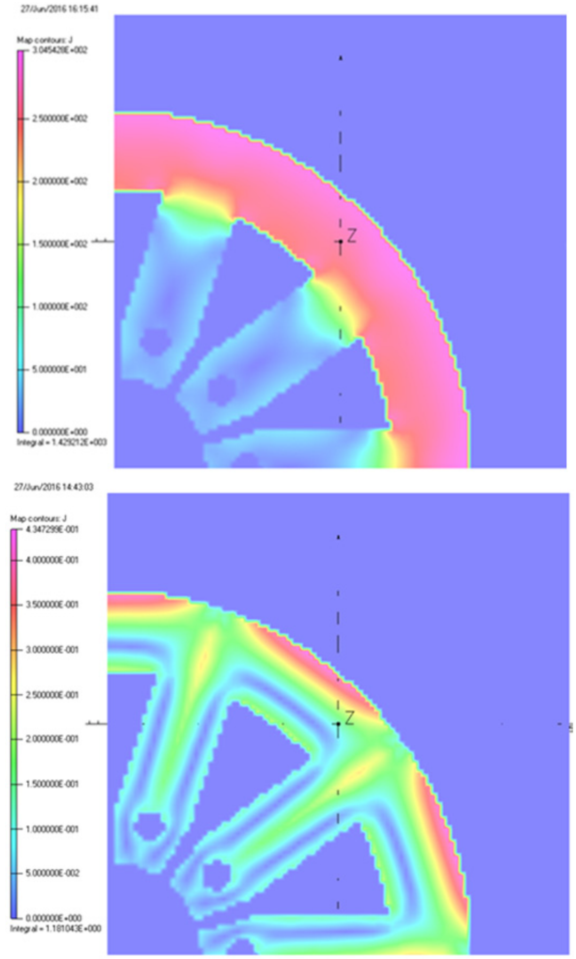

Figure 4: Contour plots of the induced Eddy current density in the anode. The upper plot (a) shows the current density without mid-vane insulation. The lower plot (b) shows the current density distribution with insulation separating the two halves of each vane along the vane radial mid-plane.

Segmenting the Anode

If the anode is segmented azimuthally and the segments are isolated from each other by insulation so that the current cannot travel around the full anode perrimeter the transient current would be reduced. If the anode is segmented along the radial mid-plane of each vane and reassembled with insulation between the vane halves, the π-mode symmetry of the RF fields is preserved. Figure 4 shows the contour plots of the induced current density of the anode for the case with 47.5 Hz sinusoidal trim coil drive current at the phase maximum. The upper (lower) plot shows induced current density for the case without (with) insulated segmentation. Figure 4a shows the large current that flows in the outer ring of the non-segmented anode. When 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 as shown in Fig. 4b. The enclosed area of each section is smaller and the central interaction region is not included.

The current density flowing normal to the radial plane midway through the cavity (half way between adjacent vanes) can be compared for the segmented and un-segmented cases. For the case without segmentation the total induced current crossing the mid cavity plane is 1440 A while the segmented case with insulation is 94 A. For the case with the 47.5 Hz drive current, segmenting the anode gives an interaction region field response to the trim coil that is 80% of the field response without anode eddy currents whereas for the non-segmented anode the field response is only 37% of the field response without the anode eddy currents.

Although this is an elegant approach to reducing the eddy currents, there are engineering issues that make this difficult to implement. The vane radial mid-plane cuts through the water cooling passage (shown in Fig. 4).

Reducing the Radial Thickness

An easier scheme to implement is to reduce the radial thickness of the outer anode ring which increases the resistance to the eddy currents, but does not affect the high frequency currents since they exist only near the surface. In this example we reduce the copper thickness to 1 mm and mechanically support the anode outer ring with 4.75 mm of stainless steel. Figure 5 shows the current induced in the all copper anode (blue) and in the anode with reduced copper width (red) as a function of frequency. The induced anode current drops significantly as the copper width is reduced. The effect on the interaction region field response is shown in Fig. 6 as a function of frequency for the all copper case (blue) and the copper-stainless steel case (red). This approach of reducing the copper thickness in the outer ring is effective in reducing the eddy current shielding of the field.

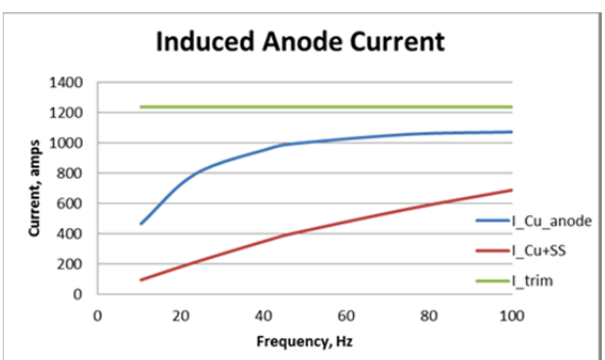

Figure 5: Current flowing in the all Cu anode (blue), the Cu+SS anode (red) and the trim coil (green) as a function of trim drive current frequency.

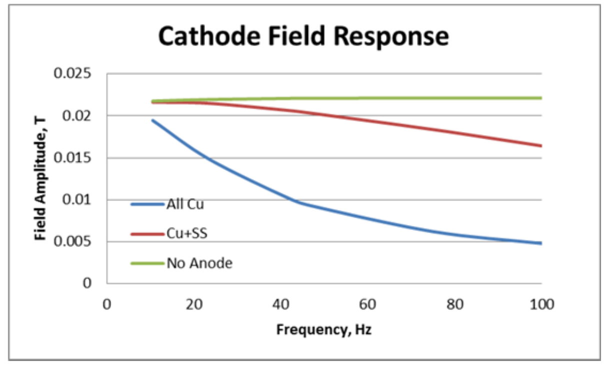

Figure 6: The interaction field response to the trim coil as a function of frequency. The blue curve represents the all Cu anode, the red curve represents the Cu+SS anode and the green curve represents the case without the anode.

Stainless Steel Anode

We have investigated using an all stainless steel anode plated with several skin depths thickness of copper. This would effectively suppress the eddy currents without affecting the high-frequency operation. There are some issues that would need to be studied for this approach. Since the thermal conductivity of stainless steel is relatively poor, there is a large temperature gradient between the inner radius of the anode and the cooling passage.

CONCLUSIONS

A magnetron using amplitude modulation is being developed as a power source for superconducting cavities. A trim coil is used to vary the magnetic field to compensate for microphonic noise. Transient eddy currents induced in the anode will tend to reduce the effectiveness of the trim coil control particularly for higher frequency noise. We have examined several approaches to reduce the eddy currents. We have found that reducing the radial thickness of the outer ring of the anode to be an effective solution.

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