EDDY CURRENT ANALYSIS FOR THE SSC LOW ENERGY BOOSTER CAVITY

Y. Goren, L. Walling, F. Brandeberry, N. Spayd
Superconducting Super Collider Laboratory†
2550 Beckleymeade Ave., MS-4010, Dallas, TX 75237

Abstract

One of the most important aspects of the SSC Low Energy Booster (LEB) cavity design is control of the eddy currents developed in the tuner during the frequency sweep. The two main difficulties created by the eddy currents are excessive tuner surface heating, and more important, a reduction in the time response of the tuner. We present a detailed analysis of the eddy currents for various tuner designs. The analysis has been done using 2D and 3D time-domain finite element codes (PE2D by Vector-Field and EMAS by MSC). Nonlinear analysis was performed utilizing B-H curves. The codes have been benchmarked analytically and by using measured data for different slotted pillbox structures.

I. INTRODUCTION

The SSCL LEB cavity is designed for a frequency sweep from 47.5 to 59.8 MHz in about 20 msec. The frequency sweep is achieved by varying a biasing magnetic field perpendicular to the r.f. magnetic field. One of the most important aspects of the design is control of the eddy currents in the tuner. The two main difficulties created by the eddy currents are excessive tuner surface heating, and more important, a reduction in the response time of the tuner to a triggered control signal. The eddy currents created on the tuner metallic surface can be reduced in two ways. First, one can slot the surface which increases the path length, or equivalently, increases the material electric resistivity. The second approach, of using a closed shell tuner with high resistive alloy, is more mechanically suited to the LEB cavity if the ferrites are liquid-cooled. This structure has the electrical disadvantage of reducing the frequency response bandwidth to about 150 Hz for the available resistive alloys. A slotted tuner is mechanically more complex but has a frequency response bandwidth in excess of 2000 Hz.

This paper presents the results of an analytical treatment of the eddy currents developed in an infinitely long metallic cylindrical shell. We show that, contrary to the widely held belief that the penetration of magnetic field into metals can be described in terms of only the skin depth, in our case the relevant parameter is the square of the skin depth divided by the shell radius. Next we present a numerical analysis of a closed shell tuner made out of Ti-6Al-4V alloy which has a high electrical resistivity as well as very good mechanical strength. This alloy yields a substantial reduction in eddy currents and more than an order of magnitude increase in frequency bandwidth compared with a copper tuner. Finally we show a numerical analysis of a slotted tuner design. It shows that contrary to another widely held belief that eddy current problems can be analyzed by the quasi-stationary approximation, that the rate of penetration of the magnetic field into the tuner through the slots depends on the displacement currents across the slots.

II. EDDY CURRENTS IN A METALLIC SHELL

First we review the results of a long thin metallic shell inside a long solenoid [1],[2]. The geometry of this setup is described in Figure 1.

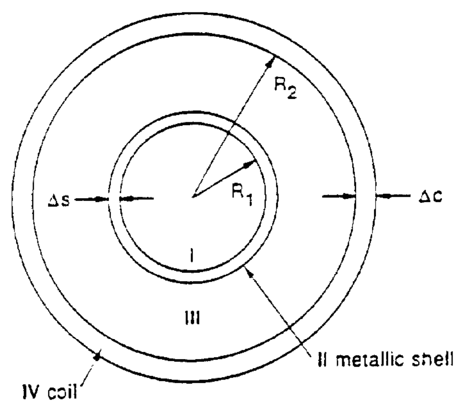

figure 1. Infinitely long metallic shell in solenoidal magnetic field

†Operated by the University Research Association, Inc., for the U.S. Department of Energy under contract No. DE-AC35-89ER40486

The axial magnetic field in region I is given by

$$B_z(t) = \mu\, \Delta_c \delta_s \exp(-\delta_s t) \int \exp(\delta_s \tau) J(\tau) d\tau \quad (1)$$

and the eddy current in the metallic shell is

$$J_{eddy} = -J\, \Delta_c/\Delta_s + \Delta_c/\Delta_s \delta_s \exp(-\delta_s t) \int \exp(\delta_s \tau) J(\tau) \quad (2)$$

The results in Eqs. (1) and (2) have been obtained assuming a spatially constant current density drive J. The parameter δ_s is defined by

$$\delta_s = 2/(\mu \sigma_0 \Delta_s R_1) \quad (3)$$

where σ_0 is the shell conductivity. The parameter δ_s in Eq. (3) measures the inverse of the magnetic diffusion time through the metallic shell. A tuner design with low eddy currents and fast magnetic time response will be characterized by the inequality $\delta_s T_{ch} >> 1$ where T_{ch} is the characteristic time scale of the drive current J. The Ti-6Al-4V alloy, with conductivity of 5.8 x 10^5 s/m, reduces the eddy-current heating to an acceptable level.

The cavity rf frequency program is achieved by biasing the ferrite. The relationship between the biasing magnetic field to the current drive determines the cavity response to a control signal. It is common to quantify the response in the frequency domain by its 3dB bandwidth. Fourier decomposing Eq. (1) we obtain the following expression for the 3 dB frequency bandwidth:

$$\Delta_f = 1 / (\pi\, \mu\, \sigma_0\, \Delta_s\, R_1) \quad (4)$$

For a 5 mm thick titanium alloy shell, this translates into a bandwidth of 292 Hz about two orders of magnitude greater than for a copper shell.

III. NUMERICAL ANALYSIS OF A CLOSED SHELL TUNER

Using the analytical results above as a guide, we simulated the closed shell LEB tuner using 2D and 3D electromagnetic codes which allow materials with a non-linear B - H curve. The maximum eddy current is developed at the top of the tuner close to the external magnetic coil. Fig. 2 describes the magnitude of the eddy current at this point as function of time. The maximum eddy current of 60 amp/cm^2 is obtained at 17 msec from the beginning of the cycle. Similar results were obtained using Eq. (2).

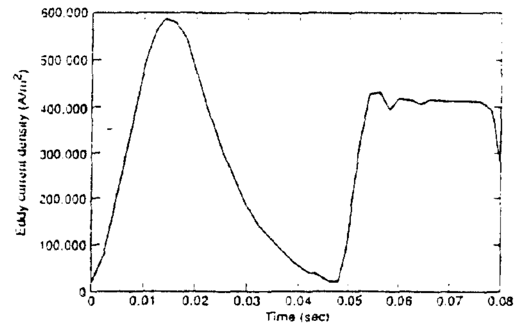

figure 2. Eddy current in Titanium tuner

In comparison, the maximum eddy current for a copper tuner is about 2700 amp/cm [2]. The thermal power, averaged over a cycle, is about 0.18 w/cm^3 which can be handled by the tuner internal coolant.

The analysis of the tuner frequency response is done numerically by sending a small ac magnetic signal on top of the dc biased field. We find that the frequency response varied across the tuner cross section with the minimum bandwidth at the bottom of the ferrites. The magnetic field vs. frequency at this location is shown in Fig 3.

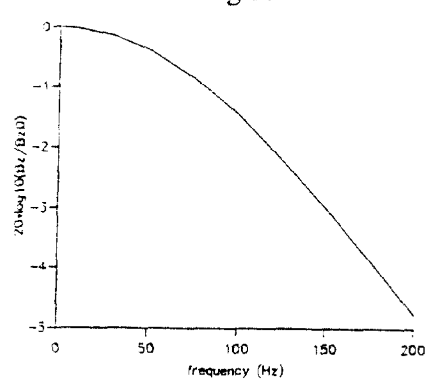

figure 3. Frequency response of Titanium tuner

It can be seen from the figure that the 3 dB bandwidth is about 140 Hz (considerably lower than the 292 Hz expected from an infinitely long metallic shell). The discrepancy corresponds to the relatively slow magnetic penetration through the side walls of the tuner. We confirmed the above results by benchmarking the code using measured data of magnetic field at various locations inside a closed stainless steel can. The narrow frequency response bandwidth led us to abandon the closed shell tuner and design a slotted tuner instead.

IV. NUMERICAL DESIGN OF A SLOTTED SHELL TUNER

The analysis of the closed shell tuner in the last section was performed using the quasi-static approximation which neglects the displacement current in Maxwell's equations. Using this approximation for the 3D problem of slotted tuner yielded a false solution in which the slots had a very small effect on the rate of magnetic penetration into the tuner. The need for the displacement currents is illustrated in Fig 4.

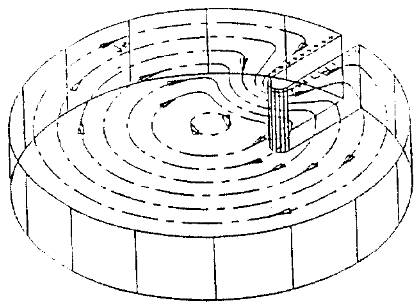

figure 4. Eddy currents around a slot

As the eddy currents approach the slot discontinuity they charge its surface. The charges create electric field which oppose the small internal field in the metal and force the currents to change direction and bypass the slot [3]. We confirmed this assumption by comparing the numerical simulation with measured results for a stainless steel can with various numbers of slots. Encouraged by these benchmark results, we designed a slotted LEB tuner. The tuner is made out of 3-mm-thick stainless steel with 16 5-mm radial slots. The slots are filled with G10 compound (dielectric material) to contain the coolant. The magnetic frequency response of this tuner is shown in Figs 5 and 6. The response function decrease slowly with frequency with a 3 dB bandwidth which exceeds 2000 Hz.

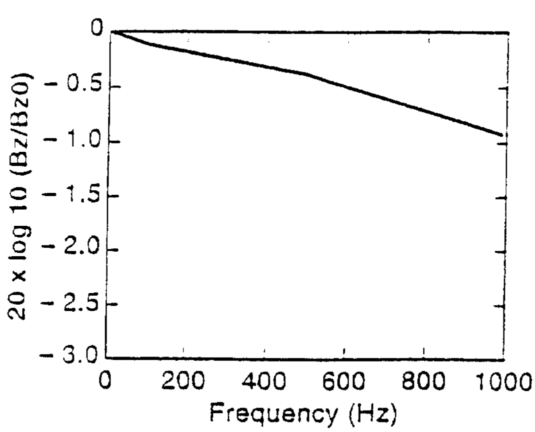

figure 5. Magnitude of magnetic frequency response

A 3-D view of the LEB tuner is shown in Fig. 7

V. SUMMARY

We presented analytical and numerical simulations of two LEB tuner designs. The surface heating due to the eddy currents are controlled in both schemes. The magnetic field frequency response of the closed shell tuner is only marginally acceptable. This lead to the slotted tuner design, which is mechanically more complex, but has the wide bandwidth required for the control system.

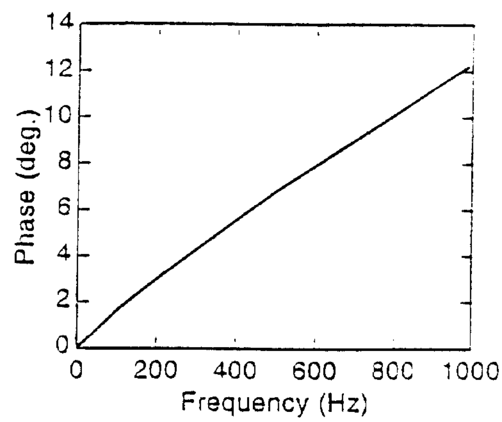

figure 6. Phase of magnetic frequency response

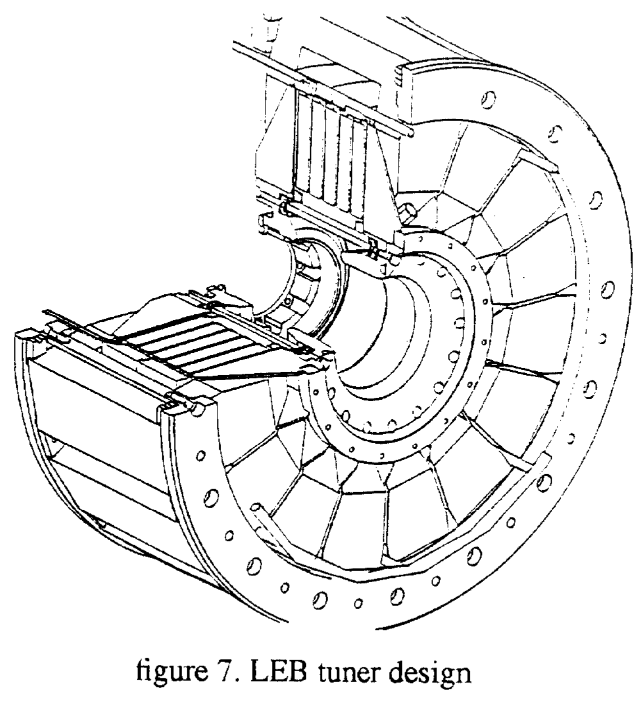

figure 7. LEB tuner design

VI. REFERENCES

[1] S. Fahy, C. Kittel, S. G. Louie *Am. J. Phys.* 56, 989 (1988)

[2] Y. Goren, B. Campbell ,SSC Laboratory, SSCL - 505, (1991).

[3] Y. Goren, L. Walling, Eddy Current Analysis, R.F. Workshop, Dallas (June 1992)