Using a Ceramic Chamber in Kicker Magnets

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Abstract

A ceramic chamber inside kicker magnets can provide the relevant field risetime. On the other hand, some metallic coating inside has to prevent static charge buildup and shield the beam from ceramic and ferrite at high frequencies to avoid possible resonances. The issues concerning the metallized ceramic chamber, such as coupling impedances and requirements on the coating, are studied to find a compromise solution for kickers of the Medium Energy Booster at the Superconducting Super Collider.

I. INTRODUCTION

There are two reasons for using ceramic chambers in kickers: (1) to avoid shielding of a fast-changing external magnetic field by metallic chamber walls; and (2) to reduce heating due to eddycurrents. On the other hand, such a chamber can produce large coupling impedances, since it works as a slow-wave structure, and can lead to accumulation of static charges on the ceramic surface. The natural way to avoid these unwanted effects is to put a thin metallic coating on the inner surface of the ceramic chamber. However, shortcomings of such a coating are obvious. It will again shield fast-changing external magnetic fields and heat the chamber walls due to eddycurrents, cf. the reasons for the ceramic chamber. To find a compromise solution we have to estimate quantitatively both the effects of shielding and impedances.

II. RISETIMES AND HEATING

The length of the front of the magnetic field pulse, τ_k, should be about 50 ns for the Medium Energy Booster (MEB) injection kicker and 2 μs for abort and extraction kickers. Even if we have a step-like external magnetic field, the risetime of the magnetic field inside a vacuum chamber with a metallic layer on the wall would be finite because of (1) shielding due to eddy-currents and (2) skin-depth effect.

A. *Shielding by Eddy Currents*

Continuous coating. For a round metallic tube of radius b and wall thickness d the risetime τ_s due to shielding of a step-like external magnetic field by eddy currents in the wall is [1, 2, 3]

$$\tau_s = \mu_0 b \sigma d/2 \ . \qquad (1)$$

The cross section of the vacuum chamber in MEB and Low Energy Booster (LEB) kickers is more similar to a rectangle 10×5 cm with rounded angles. One can easily calculate risetime τ_s for such a geometry as $\tau_s \simeq L/R$, where L and R are characteristic inductance and resistance. For metal-wall thickness d in a chamber with length l and rectangular cross section $w \times h$ ($d \ll w$, vertical magnetic field) we get $L = 4\mu_0 l/\pi$; $R = 4l/(\sigma w d)$, and hence

$$\tau_s \simeq L/R \simeq \mu_0 w \sigma d/\pi \ . \qquad (2)$$

This estimate is approximately the same as that of Eq. (1) if $w = 2b$ is assumed.

Applying Eq. (2) with w = 10 cm, we try to satisfy condition $\tau_s < \kappa\tau_k$, where κ =0.1–0.2 is a numerical factor. For $\kappa = 0.2$ this gives 99% of B_{max} inside the chamber after τ_k for a step-like external magnetic field. This leads to the following restriction

$$\sigma d < \frac{\pi\kappa\tau_k}{\mu_0 w} \ ,$$

which gives for the injection kicker with $\kappa = 0.2$

$$\sigma d < 0.25\ \Omega^{-1}; \quad \text{or} \quad \mathcal{R}_\square > 4\ \Omega\ ;$$

and for the extraction/abort ones with $\kappa = 0.1$

$$\sigma d < 5\ \Omega^{-1}; \quad \text{or} \quad \mathcal{R}_\square > 0.2\ \Omega\ .$$

Here $\mathcal{R}_\square = 1/(\sigma d)$ is the surface resistivity per square. Then the allowed thickness of the coating by stainless steel or titanium ($\sigma \simeq 1.43 \cdot 10^6\ (\Omega)^{-1}$) is $d < 0.17\ \mu$m for the injection kicker and $d < 3.4\ \mu$m for extraction/abort ones. For more accurate calculations that take into account the shape of the pulse of the external magnetic field see [4].

Coating by stripes. The shielding effect due to eddy currents can be reduced essentially if the coating by longitudinal stripes is applied instead of the continuous one, e.g. [5]. For a rectangular cross section if we have N stripes with width $w_1 = w/N$ and thickness d, $d \ll w_1$ (we neglect here the width of small gaps between stripes) on horizontal chamber walls, the resistance with respect to eddy currents is N times higher than for continuous coating, and as a result, $\tau_s \to \tau_s/N$, and the allowed value of thickness

$$d \to Nd \ .$$

The coating of side walls does not affect the shielding.

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B. Skin-Depth Effect

It is well-known that the skin-depth in a metal is equal to $\delta = \sqrt{2/(\mu_0\sigma\omega)}$. If the metal-wall thickness is d and frequency ω_{sd} is defined by the equation $\delta(\omega_{sd}) = d$, all frequencies higher than ω_{sd} will be screened by the wall. It gives us the risetime due to skin-depth effect

$$\tau_{sd} = \omega_{sd}^{-1} = \mu_0\sigma d^2/2 . \qquad (3)$$

To satisfy condition $\tau_s < \kappa\tau_k$, it is necessary to restrict

$$\sigma d^2 < 2\kappa\tau_k/\mu_0 .$$

For the injection kicker we get $\sigma d^2 < 0.016$ m/Ω and for stainless steel $d < 100$ μm. The limitation from the skin-depth effect is weak in comparison with those from the eddy currents.

C. Heating Due to Eddy Currents

The energy produced by eddy currents during time τ in the wall of length l, width w and thickness d can be estimated as

$$E \simeq \frac{B_0^2\sigma d w^3 l}{12\tau} , \qquad (4)$$

where $\dot{B} \simeq B_0/\tau$ is taken. The relevant temperature rise is

$$\Delta T \simeq \frac{E}{CM} \simeq \frac{B_0^2\sigma w^2}{12\tau c_m\rho_m} , \qquad (5)$$

where c_m and ρ_m are specific heat and density of the wall material. If we take them as 450 J/kg/K and 7800 kg/m^3 for stainless steel, $B_0 = 0.015$ T, $\tau = 50$ ns, we get $E/l = 0.5$ J/m for $d = 1$ μm, and $\Delta T = 1.5$ K. That is not too much. It should be noted also that ΔT is independent of the thickness of the coating.

For N metallic stripes instead of a solid coating, the induced eddy current in each stripe is $I_1 = I/N^2$ and the resistance of a stripe is $R_1 = NR$. The total energy released is only $E_N = E/N^2$ and, hence, $\Delta T_N = \Delta T/N^2$. It means that in the case of $N = 20$ stripes we have the temperature rise $\Delta T = 0.004$ K only.

D. Effects of Slots in Metallic Coating

Let us consider what width w_1 of stripes and g of gaps between them are reasonable if the metallic coating is performed as stripes. If there are N stripes on a horizontal chamber wall, then $w_1 + g = w/N$ and the allowed thickness of coating is $d = Nd_0$, where w is the width of chamber and d_0 is the allowed thickness of continuous coating. When $d_0 \simeq 0.15$ μm for stainless steel and $w = 10$ cm we would get reasonable figures $d = 3$ μm and $w_1 + g = 5$ mm for $N = 20$. As for ratio g/w_1, it can be estimated as follows. A narrow ($g \ll w_1$) gap between two thin stripes ($d \ll g$), which are in one plane, has capacitance

$$C \simeq \frac{\varepsilon + 1}{2}\frac{4\varepsilon_0 l}{\pi}\ln(2w_1/g) ,$$

where l is the gap length. If g is very small, this capacitance is big, and eddy currents at high frequencies would easily flow between stripes, shielding the external magnetic field strongly, as it occurs with a continuos coating. At $\omega \simeq 5/\tau_k = 10^8$ s^{-1} and $l = 26$ cm (the length of one section of the MEB injection kicker), $Z_C = 1/(\omega C) \simeq 300\,\Omega$ for $w_1/g = 4$. It should be compared with the resistance of a stripe $R \simeq 60\,\Omega$ and its reactance $Z_L = \omega L \simeq 42\,\Omega$. It is clear that from the point of view of shielding we have to restrict the ratio $w_1/g \leq 10$–15 in this case. It means that reasonable values for the stripe and gap width are $w_1 = 4.5$ mm and $g = 0.5$ mm for the case of $N = 20$.

III. COUPLING IMPEDANCES OF CERAMIC CHAMBER

To estimate impedances of ceramic chamber we will use a model with a circular cross section of inner radius b and multi-layer wall: inner metal coating of thickness d (conductivity σ), ceramic of thickness Δ (permittivity ε), and thick outermost layer (perfect conductor or magnet). For such a geometry, it is possible to calculate em-fields produced by a given current perturbation and to derive explicit expressions for coupling impedances. The longitudinal impedance was done by B. Zotter [6].

A. Low-Frequency Impedances

The real part of the longitudinal impedance of a chamber piece with length L is

$$Re\, Z(\omega) = \frac{L}{2\pi b}\mathcal{R}$$

where at low frequencies ($\delta > d$) $\mathcal{R} = \mathcal{R}_\square = 1/(\sigma d)$. Since it works when $f < f_{rev} = 75.7$ kHz, the ratio of the kicker resistive-wall impedance to that of the ring is

$$r = \frac{Re\, Z_{kick}}{Re\, Z_{ch}} = \frac{L}{2\pi R}\frac{d_{ch}\sigma_{ch}}{d\sigma} ,$$

where $2\pi R = 3960$ m is the MEB circumference and $d_{ch} = 2$ mm is the wall thickness. The transverse impedance can be obtained making use of the relation $Z_\perp = (2R/b^2)Z/n$. With $L = 3$ m as the total length of the injection kicker, $\sigma_{ch} = \sigma$ and $d = 0.15$ μm, we get $r \simeq 13$ (!). Certainly, it is the worst case since we assume the image current flows only through the coating. In fact, some part of it will flow through external circuits. Nevertheless, for N stripes this ratio would be N times lower since the allowed thickness is N times higher. Otherwise, in the case of a solid coating it is reasonable to connect two pieces of the beam pipe, those upstream and downstream the kicker, by a good external conductor to prevent the essential reduction of the resistive-wall instability risetime.

In the so-called low-frequency limit, i.e., when $\omega \ll c\gamma/(\sqrt{\varepsilon}b)$, the longitudinal impedance of the uncoated chamber ($d = 0$) is [6]

$$\frac{Z}{n} = \frac{Z_0 L}{2\pi R}\left[\frac{1}{\varepsilon}\tan\delta_\varepsilon - i(\beta^2 - \frac{1}{\varepsilon})\right]\ln\left(1 + \frac{\Delta}{b}\right) , \qquad (6)$$

where $\tan\delta_\varepsilon$ is the loss-tangent (10^{-4} for alumina), and a perfect conductor outside ceramic is assumed.

From similar calculations the transverse impedance of the uncoated ceramic chamber with a perfect conductor outside ceramic is

$$Z_\perp = \frac{Z_0 L}{2\pi b^2}\left[\frac{2\varepsilon\tan\delta_\varepsilon}{(\varepsilon+\alpha)^2} - i\left(\frac{\varepsilon-\alpha}{\varepsilon+\alpha} - \frac{\beta^2 b^2}{(b+\Delta)^2} - \frac{1}{\gamma^2}\right)\right] ,$$

where

$$\alpha = \frac{(b+\Delta)^2 - b^2}{(b+\Delta)^2 + b^2} .$$

The transverse impedance in the case when a perfect magnet is outside ceramic is

$$Z_\perp = \frac{Z_0 L}{2\pi b^2}\left[\frac{2\varepsilon\tan\delta_\varepsilon}{(\varepsilon+1/\alpha)^2} - i\left(\frac{\alpha\varepsilon-1}{\alpha\varepsilon+1} + \frac{\beta^2 b^2}{(b+\Delta)^2} - \frac{1}{\gamma^2}\right)\right] .$$

For the case of inner continuous coating we have simple expressions in the low-frequency limit $\omega < c/(\sqrt{\varepsilon}b)$ when $\gamma \gg 1$ and, in addition, $\varepsilon\varepsilon_0\omega b/\sigma \ll d \ll \delta$. For stainless steel at frequency $f = 60$ MHz it means 10^{-9} m $\ll d \ll 5.4\cdot10^{-5}$ if $\varepsilon = 10$, i.e., the interval of practical interest. The transverse impedance is

$$Z_\perp = Z_0\frac{L}{2\pi b^2}\frac{s - i\zeta}{s^2+\zeta^2} , \qquad (7)$$

where $s = bd/\delta^2$ and $\zeta = (b+\Delta)^2/[(b+\Delta)^2 \mp b^2]$, the upper sign corresponds to the case when a perfect conductor is outside ceramic, and the lower one to a perfect magnet.

Now one can make some estimates. Let us take b = 2.5 cm for a *pessimistic* estimate and b = 5 cm for an *optimistic* one, $\Delta = 3$ mm, $\varepsilon = 10$, $\gamma = 13$–213, $R = 630$ m and $L = \Sigma N_i L_i = 21$ m, the total length of all MEB kicker magnets. The impedance values at $f = 60$ MHz, which corresponds to the bunch spacing 5 m, are shown in Tables 1 and 2.

Table 1
Longitudinal Impedance

	(Z/n)/ mΩ		
d, μm	0	1	5
$b = 2.5$ cm	$?-i202$	$88 - i51$	$23 - i3$
$b = 5$ cm	$?-i104$	$46 - i25$	$12 - i1$

Table 2
Transverse Impedance

	$Z_\perp$/ (kΩ/m)		
d, μm	0	1	5
	injection kicker		
$b = 2.5$ cm	$?-i243$	$34 - i2$	$7 - i0.1$
$b = 5$ cm	$?-i44$	$4 - i0.1$	$0.9 - i0.005$
	extraction & abort kickers		
$b = 2.5$ cm	$?-i310$	$152 - i89$	$40 - i5$
$b = 5$ cm	$?-i42$	$20 - i11$	$5 - i0.5$

Here "?" in the first column means that the real part of impedance for an uncoated chamber is defined mostly by losses in external conductors or ferrite.

At frequencies below 1 MHz $Im\,Z/n$ and $Im\,Z_\perp$ are nearly frequency- and d-independent: -0.17 Ω and -0.35 MΩ/m for the extraction and abort kickers together; -0.26 Ω and -0.52 MΩ/m for the injection one, when $b = 2.5$ cm is taken. With $b = 5$ cm (optimistic estimate), we get the same values of $Im\,Z/n$, and -0.09 MΩ/m and -0.13 MΩ/m for $Im\,Z_\perp$, respectively.

B. *Resonances*

Since the ceramic chamber works as a slow-wave structure, some resonances can occur at high frequencies. If we consider $\tan\delta_\varepsilon \ll 1$ and frequency range $c/(\sqrt{\varepsilon}b) \ll \omega \ll c\gamma/b$, the resonance condition is simplified to [6]

$$\cot|\nu|\Delta = b|\nu|/(2\varepsilon) , \qquad (8)$$

where $\nu = \omega\sqrt{1-\varepsilon\mu\beta^2}/c$. If, in addition, $b/(2\varepsilon\Delta) \ll 1$, the p-th resonance is approximately defined by $z_p \equiv |\nu_p|\Delta \simeq \pi(p-1/2)$. The maximal value of the longitudinal impedance at the resonance can be estimated as

$$\left(\frac{Z}{n}\right)_p = \frac{L}{2\pi R}\frac{8Z_0}{\tan\delta_\varepsilon}\frac{\beta^2\Delta^3}{z_p^2 b^3}\frac{(\varepsilon-\beta^{-2})^2}{z_p^2 + C} , \qquad (9)$$

where $C = x[x + 2/(\varepsilon\beta^2) - 1]$ with $x = 2\varepsilon\Delta/b$. For the parameters cited above we get the lowest ($p = 1$) resonance frequency $f_1 \simeq 8.6$ GHz and corresponding maximal impedance $(Z/n)_1 \simeq 16$ kΩ if $L = 21$ m.

The metallic coating damps these resonances drastically. The impedance value is approximately

$$\frac{Z}{n} = Z_0\frac{L}{2\pi R}\frac{\delta^2}{2bd} , \qquad (10)$$

which gives $(Z/n)_1 \simeq 1.2$ mΩ for $d = 1$ μm.

IV. CONCLUSIONS

The inner metallization of the ceramic chamber in kickers helps to avoid resonances and static charge buildup. For very fast kickers the coating by stripes has some advantages.

V. REFERENCES

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