LA--10223-MS

DE85 001521

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by

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ABSTRACT

The rapidly changing magnetic fields of the LAMPF II rapid-cycling synchrotron will induce electric fields that will induce ohmic heating by wall currents in a beam pipe placed within these rapidly changing fields. A conducting beam pipe is required to remove high-frequency collective instabilities. Some compromise in design is required so that a beam pipe with low conductivity at the LAMPF II cycling frequency ($f = 30\text{-}60\text{ Hz}$) and high conductivity at high frequencies ($f \gtrsim 10\text{-}100\text{ MHz}$) is obtained.

I. BEAM PIPE HEATING

The dominant magnetic field in LAMPF II is the rapidly changing dipole field, which we represent as

$$\vec{B} \cong (\bar{B} + B_0 \sin(\omega t + \phi)) \hat{y}, \quad (1)$$

where $\hat{y}$ is a unit vector and for typical designs, $\bar{B} \cong B_0 \cong 0.5\text{T}$. For $f = 30\text{ Hz}$, $\omega = 188.5\text{ s}^{-1}$.

From Maxwell's Equations ($\nabla \times \vec{E} = -d\vec{B}/dt$), we obtain an induced longitudinal electric field

$$\vec{E} = -\omega x B_0 \sin \omega t \hat{z}. \quad (2)$$

We assume that the beam pipe is a conducting hollow cylinder of radius r , resistivity ρ , and thickness d , with d much less than a skin depth at 30 Hz. The current induced in the pipe is found from $\vec{j} = \sigma \vec{E}$, and the power per unit pipe length dissipated in the conductor is

$$P' = \left| \int \langle \vec{j} \cdot \vec{E} \rangle dA \right| , \quad (3)$$

or

$$P' = \left| \sigma \omega^2 \int B_0^2 x^2 \langle \sin^2 \omega t \rangle dA \right| ,$$

or

$$P' = \frac{\pi}{2} \sigma \omega^2 r^3 B_0^2 d \quad \text{W/m} ,$$

where $\sigma = 1/\rho$ is the conductivity. With $r = 0.05$ m, and $\rho = 1.7 \times 10^{-8} \Omega \cdot \text{m}$ (copper) and $d = 10^{-3}$ m, we obtain $P' = 1.03 \times 10^5$ W per meter or ~ 50 MW in a 500-m circumference ring. This is unacceptably high. The losses can be reduced to manageable levels by use of a lower conductivity metal such as stainless steel ($\rho = 73 \times 10^{-8}$), or nichrome ($\rho = 100 \times 10^{-8}$), and a thinner pipe.

If we set a limit on power losses of 0.25 MW total, we require $P' < 0.50$ kW/m or $d \lesssim 4.8 \times 10^{-6}$ m for copper, $d \lesssim 200 \times 10^{-6}$ m for stainless steel. A somewhat higher limit may be tolerable, although a lower limit would lower power costs.

II. COLLECTIVE INSTABILITY CONSTRAINTS

Application of the Boussard¹ criterion to LAMPF II parameters leads to a limit on the longitudinal impedance

$$\left| \frac{Z}{n} \right| \lesssim 20 \Omega . \quad (4)$$

Pellegrini and Wang² have shown that this limit is applicable in the "high-frequency, fast-blowup" regime for bunched beams, that is, for frequencies greater than the inverse bunch length ($n = \omega/\omega_0 \gtrsim 300$). The high-frequency impedance is usually dominated by a "broad-band-resonator" impedance with critical frequency at the beam pipe cutoff ($n_c = \omega_c/\omega_0 \cong R/2r \cong 3000$ for LAMPF II). We require that the resistive wall contribution be much smaller than the above limit so that it cannot contribute to the instability in Eq. (4):

$$\left| \frac{Z}{n} \right| \text{ (resistive wall)} \lesssim 2 \Omega . \quad (5)$$

The calculation of Z/n can be separated into two regions; one where the skin depth δ is much greater than the conductor thickness d , and a high-frequency regime ($\delta \ll d$).

In the low-frequency regime ($d \ll \delta$),

$$\frac{Z}{n} \cong \frac{\omega_0}{\omega} \left(\frac{\rho R}{rd} \right) \cong \frac{1}{n} \left(\frac{\rho R}{rd} \right) . \quad (6)$$

In the high-frequency region ($\delta \ll d$), we find

$$\frac{Z}{n} \cong (1 - i) \left(\frac{\omega_0}{\omega} \right) \frac{R\rho}{r\delta} \text{ with } \delta = \sqrt{\frac{2}{\omega\sigma\mu}} , \quad (7)$$

so that

$$\frac{Z}{n} = \frac{(1 - i)}{\sqrt{2n}} \frac{\sqrt{Z_0 \rho R}}{r} . \quad (8)$$

The two formulae differ by only $\sqrt{2}$ in the intermediate region ($d \cong \delta$); we ignore this factor in this approximate analysis. The table and figure show the impedance as a function of frequency for copper and stainless steel.

RESISTIVE WALL IMPEDANCE OF AN ACCELERATOR-RING BEAM PIPE

R = 100 m, r = 0.025 m		
Quantity	Good conductor (Copper)	Fair Conductor (Stainless Steel)
$\delta(\omega)$	$0.095/\sqrt{n}$ (mm)	$0.620\sqrt{n}$ (mm)
$ \frac{Z}{n} $ ($d < \delta$)	$\frac{0.068}{n d}$ Ω (mm)	$\frac{2.92}{n d}$ Ω (mm)
$ \frac{Z}{n} $ ($\delta < d$)	$\frac{1.01}{\sqrt{n}}$ Ω	$\frac{6.62}{\sqrt{n}}$ Ω

Resistive wall impedance.

If we require $Z/n \lesssim 1 \Omega$ for $n \gtrsim 100$, we find $d \gtrsim 0.27 \times 10^{-3}$ mm for copper and $d \gtrsim 0.012$ mm for stainless steel. If we also require $d \gtrsim \delta$ for $n \gtrsim 100$, we find $d \gtrsim 8.5 \times 10^{-3}$ mm for copper and $d \gtrsim 0.056$ for stainless steel. The second requirement would imply somewhat greater power dissipation than desired (~ 1 kW/m) for copper, but only 0.15 kW/m for stainless steel.

III. CONCLUSIONS AND DISCUSSION

A thin metal beam pipe can provide adequate shielding for collective instabilities without excessive ohmic heating for LAMPF II. The thinness desired (5 μ for copper; 100 μ for stainless steel) indicates that it might be most easily obtained by plating the inside of a ceramic pipe. Compromise between resistivity requirements and mechanical construction constraints indicates a "poor" conductor like stainless steel or nichrome is preferred, because the thickness required for a good conductor ($\lesssim 5$ microns) appears difficult to deposit uniformly. A layer of 50-100 microns (2-4 mils) of nichrome or similar conductivity metal appears to be about the best choice.

REFERENCES

1. D. Boussard, CERN report, LAB II/RF/Int/75-2 (1975).
2. C. Pellegrini and J. C. Wang, Proc. XI Int. Conf. on High Energy Particle Accelerators, p. 554 (1980).