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SHIELDING AGAINST MAGNETIC RADIATION LOSS FROM A HOT PLASMA

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ABSTRACT

Classical electromagnetic theory indicates that a conducting metallic shield can reduce the magnetic-radiation loss from a hot plasma (centrally located) undergoing D-D burn to less than 1%, or two orders of magnitude.

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1. INTRODUCTION

Some concern has been expressed over the possibility that the magnetic radiation, i.e., the radiation from charges spiralling in a magnetic field, might cool a plasma rapidly enough to make a D-D fusion burn impossible in any device of reasonable size.[1] The present paper concerns the possibility of using a metallic shield to return this magnetic-radiation energy back to the plasma.

2. FREQUENCY RANGE

A charge spiralling around lines of magnetic induction has a gyromagnetic frequency given by $\nu = eB/2\pi m$. For fields necessary to confine a plasma undergoing D-D burn (10^4 to 10^5 gauss), the electron frequency becomes $\nu = 3 \times 10^{10}$ or 3×10^{11} cycles/sec. Including harmonics, the frequencies of interest may extend to the order of magnitude of 3×10^{12} cycles/sec. For frequencies less than 3×10^{13} cycles/sec, however, ordinary metals behave as excellent reflectors[2] or classical conductors. Consequently, for shielding against magnetic-radiation-energy loss, we need consider only ordinary metallic shielding.

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[1] B. A. Trubnikov and V. S. Kudryavtsev, Plasma Radiation in Magnetic Field. Second U.N. International Conference on the Peaceful Uses of Atomic Energy, A/CONF. 15/P/2213, USSR, 8 August 1958.

[2] J. A. Stratton, Electromagnetic Theory (McGraw-Hill Book Company, New York, 1941), p. 505-511. The value of the constant in Eq. (86) is $\sqrt{4\pi\epsilon} = 1.054 \times 10^{-5}$ and not 2.11×10^{-4}. Similarly, the constant in Eq. (89) should be 2.11×10^{-5} and not 4.22×10^{-4}. The table on page 508 should be ignored unless the original article (Hagen and Rubens, Ann. Physik 11, 873 (1903) is read. B. I. Bleaney and B. Bleaney, Electricity and Magnetism (Oxford at the Clarendon Press, 1957), p. 257-259.

3. GEOMETRY

If we assume that the hot plasma, which occupies some central position, is surrounded by a vacuum and then by a metallic shield, the details of the geometry are largely immaterial. To illustrate this fact, we consider a sphere of hot plasma of radius R, surrounded by vacuum and then a metallic shield of radius R_2. If the magnetic-radiation flux from the plasma is f_1, the radiation flux incident upon the shield will be

$$f_2 = f_1 R_1^2/R_2^2 . \tag{1}$$

If the reflectivity of the surface is assumed to be r, the flux reflected at the shield will be

$$f_2' = r f_2 . \tag{2}$$

The flux that is incident upon the plasma is then

$$f_1' = f_2' R_2^2/R_1^2 = rf_1 , \tag{3}$$

where Eqs. (1) and (2) have been used.

We may assume the plasma to be an ideal absorber of the magnetic radiation. Not only is the surface of the plasma capable of the inverse process of radiating magnetically, but the interior of the plasma, being highly ionized, will also be a good absorber. In addition, if some flux were transmitted through the plasma, it would have the effect, mathematically speaking, of merely increasing the original magnetic-radiation flux from the plasma by a few percent. The net flux of energy lost from the device is then given by

$$\Delta f = f_1 - f_1' = (1 - r)f_1 , \tag{4}$$

or the fractional flux loss is

$$\Delta f/f = 1 - r . \tag{5}$$

It appears that Eq. (5) will be valid for any plasma located centrally to a reasonable degree. Consequently, the geometry is largely immaterial when the reflectivity of the shield, r, is known. The geometry becomes important only when the temperature of the shield must be determined in order to determine r.

4. REFLECTIVITY r

Since we are within a frequency range for which a classical electromagnetic treatment[2] is valid, we use the formula

$$r = 1 - 2.11 \times 10^{-5} \sqrt{K_m \nu \rho} \ , \qquad (6)$$

where ρ is the resistivity of the metal in ohm-meter and $K_m = \mu/\mu_0$ is the magnetic permeability which is unity for most metals. At the worst, we need consider $\nu \approx 3 \times 10^{12}$ cycles/sec, which gives

$$r = 1 - 36.5 \sqrt{K_m \rho} \ . \qquad (7)$$

For silver (99.98 percent pure), the resistivity is 1.63×10^{-8} ohm-meter at 20°C which gives an absorption, $(1-r)$, of 4.66×10^{-3}. For copper with a resistivity of 1.72×10^{-8} ohm-meter at 20°C, the fraction absorbed is 4.80×10^{-3}. For iron with a resistivity of 2×10^{-7} ohms/meter at 20°C and a permeability of 10^3 (it is actually less for high frequencies), the fraction absorbed is 0.516 (indicating that, perhaps, iron should be avoided).

Thus, if a good conductor is used, it appears that at least 99 percent of the magnetic radiation can be returned to the plasma. This reduces the loss due to magnetic radiation by at least a factor of 100, or two orders of magnitude.

5. SHIELD TEMPERATURE

The reflectivity of the shield depends upon the temperature of the shield through the resistivity, Eq. (6). Since the resistivity is a linear function of the temperature except for very low temperatures, the reflectivity Eq. (6) or (7) varies as the square root of the temperature. We have

$$r = 1 - 2.11 \times 10^{-5} \left[K_m \nu \rho_0 (1 - \alpha t)\right]^{1/2} \ , \qquad (8)$$

where ρ_0 is the resistivity at 0°C, t is the centigrade temperature, and α is the temperature coefficient.

To decrease the magnetic radiation loss, the temperature of the shield should be maintained as low as possible. Considering the thermal conduction of heat from the inside of a spherical shield (of radius R_2 and thickness ΔR) at a temperature t_1 to the outside of the shield at a temperature t_2, we obtain, for the temperature of the inside of the shield,

$$t_1 = t_2 + \Delta f_2 \, \Delta R / k \ , \qquad (9)$$

where k is the thermal conductivity of the shield and Δf_2 is the magnetic-radiation flux absorbed by the shield,

$$\Delta f_2 = f_2 (1-r) = f_1 (1-r) R_1^2/R_2^2 . \qquad (10)$$

Substituting Eq. (10) into Eq. (9), we obtain

$$t_1 = t_2 + (f_1 R_1^2) \frac{\Delta R}{R_2^2} \left(\frac{1 - r}{k}\right).$$

Since $f_1 R_1^2$ is just $1/4\pi$ times the total magnetic-radiative power of the plasma source, it may be regarded as constant. The temperature t_1 may thus be reduced by: decreasing t_2, increasing R_2, and choosing a good reflecting and heat-conducting shield. For ordinary temperatures, silver has both the best reflectivity (see Section 4) and the best thermal conductivity.

Since the temperature t_2, the size of the shield, R_2, and the thickness of the shield, ΔR, must be chosen for convenience and strength, the complete engineering problem is complicated and beyond the scope of the present paper.

The reflectivity as a function of temperature may be sampled by considering a few cases which are listed in Table I.

Table I

Absorptivity $1-r$ for $\nu = 3 \times 10^{12}$ cycles/sec

Metal	–259°C	–200°C	20°C	High Temp
silver	3.46×10^{-4}	2.18×10^{-3}	4.66×10^{-3}	(750°C) 0.94×10^{-2}
copper	4.32×10^{-4}	1.70×10^{-3}	4.80×10^{-3}	(1000°C) 1.12×10^{-2}
aluminum	---	2.68×10^{-3}	6.13×10^{-3}	(400°C) 1.03×10^{-2}

These values were obtained from Eq. (7) where, for the metals considered, K_m has the value 1. The resistivities were taken from the Handbook of Chemistry and Physics.[3] The values in the table are representative of the temperature variation for most metals.

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[3] Handbook of Chemistry and Physics, C. D. Hodgman, Ed., Thirty-fourth Edition (Chemical Rubber Publishing Co., Cleveland, Ohio, 1952), pp. 2186-92.

From an examination of the table, it is apparent that the reflectivity is not particularly dependent upon temperature, except for extremely low temperatures where a marked improvement occurs. Unless one is willing to try to obtain these low temperatures, the temperature of the shield may be neglected, and it may be assumed that an absorption of somewhat less than 1 percent occurs.

6. CONCLUSIONS

It may be concluded that the magnetic radiation loss may be easily reduced by a factor of about 5×10^{-3} by using a good conducting shield. If any significant improvement over this figure is desired, elaborate methods must by employed to cool the shield to very low temperatures of the order of 5 to 10 degrees absolute. Since no measurements have been made of the actual flux of magnetic radiation from a plasma, and since there is some doubt that the flux will, indeed, be large, there is no need to suggest anything other than a simple metallic shield at this time.

Such a shield will also be effective and desirable for shorter-wave-length radiation (visible).

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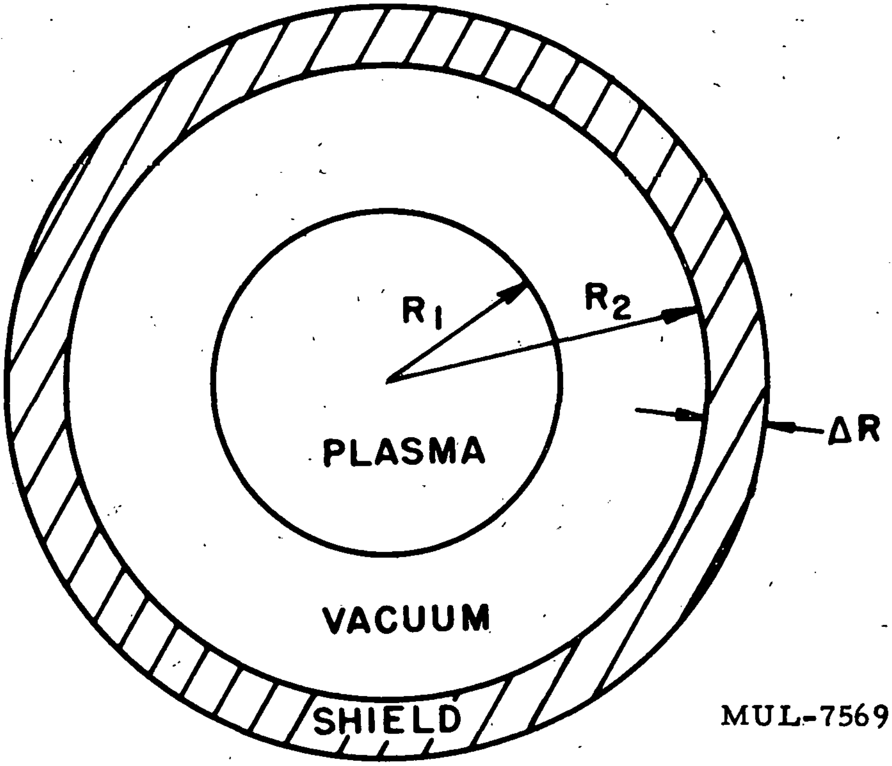

Fig. 1. Spherical model of hot plasma surrounded by vacuum and metallic shield.