DESIGN GUIDELINES FOR FERRITE ABSORBERS SUBMITTED TO RF-INDUCED HEATING

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Abstract

The use of ferrite absorbers is one of the most effective means of damping potentially harmful high order RF modes, which may lead to beam instabilities and excessive power losses in accelerator devices. However, the power deposited on ferrite absorbers themselves may lead to ferrite exceeding its Curie temperature, losing its damping properties. An evaluation of the ferrite capability to dissipate deposited heat is hence of paramount importance for the safe design of particle accelerator devices. In this paper, figures of merit are proposed to assess the maximum specific power allowed on a generic ferrite tile, before it reaches its Curie temperature. Due to its inherent brittleness, sufficient contact pressure between ferrite and its housing, allowing heat transmission by conduction, can hardly be applied. A semi-analytical study is thus performed, assuming that ferrite is evacuating heat solely through radiation. The described method is then exemplified in the case of the BPM-embedded tertiary collimator (TCTP) designed in the framework of the LHC collimation upgrade.

INTRODUCTION

Any abrupt change of the LHC machine aperture can potentially cause harmful High Order Modes (HOM) resonation. One possible solution is to reduce volume discontinuities seen by the beam, thus avoiding the onset of such modes, by ensuring continuity and gradual transitions between dissimilar adjoining volumes with so-called RF fingers. An alternative approach relies on adding absorbers made of high magnetic loss materials damping HOM in the regions where they develop; typical material of choice for such absorbers is ferrite, a hard, brittle ceramic made from iron oxides. A list of ferrite grades typically used at CERN for HOM damping applications is provided in Table 1.

In 2012, operation in the LHC was pushed to higher beam intensity and shorter bunch spacing. Several components embedding ferrite absorbers experienced significant beam-induced RF heating, with ferrite sometimes reaching its Curie temperature (T_C), which eventually led to beam downtime. Sudden pressure increases within Ultra-High Vacuum (UHV) equipment, due to outgassing from overheated ferrite, were also observed [1].

The analysis presented falls among the actions taken within the scope of the LHC RF Fingers (LRFF) task force [2], which was created to deal with such unexpected RF-related overheating and aims at obtaining a figure of merit for determining the cooling efficiency of any given ferrite configuration.

Table 1: Typical Ferrite Grades for RF Applications.

Supplier	Grade	T_C [K]	Type	ε_F [-]
Trans-Tech	TT2-111R	648	$NiZnFe_2O_4$	0.8
Ferroxcube	4E2	673	$NiZnFe_2O_4$	
	4S60	373		
	8C11	398		

GENERAL CASE

Once RF absorbers placed in UHV equipment start heating, thermal transfer can only be performed by conduction and radiation. On the other hand, ferrite properties (low tensile strength, high brittleness) make it incompatible with the high contact pressure required to ensure good exchange by conduction with a heat sink. Therefore, radiation can usually be considered as the only effective heat transfer mechanism.

Figure of Merit Determination

The problem of heat transfer can be tackled in a simplified way by resorting to the equation of heat radiation between two grey bodies forming an enclosure [3].

$$Q = \frac{\sigma_B (T_F^4 - T_0^4)}{\frac{1-\epsilon_F}{A_F \epsilon_F} + \frac{1}{A_F F_{0F}} + \frac{1-\epsilon_0}{A_0 \epsilon_0}} \quad [W] \qquad (1)$$

where σ_B: Boltzmann constant
F_{0F}: ferrite view factor

Eq. 1 can be extensively applied provided the following assumptions are made:

i) System in steady-state condition.
ii) Heat sink with uniform emissivity (ε_0) and absolute temperature (T_0).
iii) Heat sink with surface A_0 completely surrounding the ferrite tile(s), with no intermediate components at different temperatures and emissivity (i.e. $F_{0F} = 1$).
iv) Ferrite tile(s) with uniform emissivity (ε_F) and absolute temperature (T_F).

In some real systems, iii) may become a relatively restrictive requirement; however, for the intent of this analysis, it represents an acceptable assumption. The hypothesis of bulk ferrite temperature (iv) is acceptable since heat diffusion time constants inside the ferrite are much shorter than time required to reach steady-state condition through radiation.

Normalization of Eq. 1 with respect to ferrite surface (A_F) leads to Eq. 2, which provides the ferrite specific heat evacuation capacity, i.e. the radiated heat per unit surface of the ferrite absorber.

$$Q^* = \sigma_B(T_F^4 - T_{F0}^4)K_{\varepsilon A} \quad [W/m^2] \qquad (2)$$

where

$$K_{\varepsilon A}(\varepsilon_0, \varepsilon_F, K_A) = \frac{1}{\frac{1-\epsilon_F}{\epsilon_F} + 1 + \frac{1-\epsilon_0}{K_A \epsilon_0}}$$

and

$$K_A = \frac{A_0}{A_F}$$

A figure of merit (Q^*) has thus been defined, which is only function of material properties and of the ratio K_A between exchanging surfaces and can be extended to any geometry, from bulk elements of different shapes to long tiles of arbitrary cross section. The only restriction is given by ferrite concave shapes; in such case the simplification on the view factor, triggered by assumption iii), cannot be performed, thus some knowledge on the geometry must be introduced in the analysis.

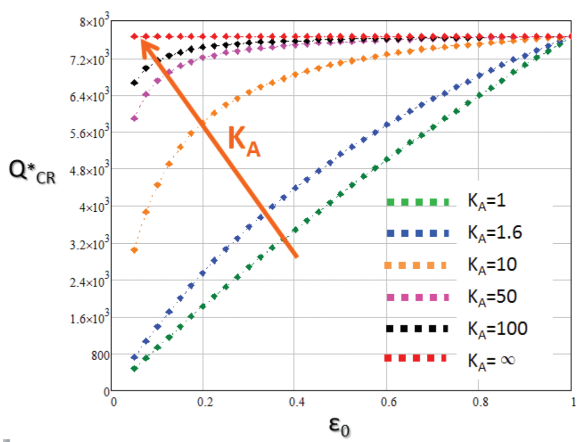

Figure 1: Q^*_{CR} [W/m²] vs. ε_0 [-] for different K_A.

We now define Q^*_{CR} as the value of Q^* for which ferrite Curie temperature is reached. In Fig. 1, Q^*_{CR} is plotted as a function of heat sink emissivity and K_A. The curves represent the heat evacuation capacity for a ferrite tile with $\varepsilon_F = 0.8$ and $T_F = 648$K (grade TT2-111R) and a heat sink at 295K.

It can be seen how, for small values of K_A (around 1), Q^*_{CR} is very sensitive to variations of ε_o; in this case, one should try and maximize the emissivity of the heat sink. On the other hand, as K_A grows, Q^*_{CR} rapidly reaches an asymptote: for $K_A \to \infty$, Q^*_{CR} becomes independent of ε_o. Hence, it is not necessary to aim at high values of heat sink emissivities when K_A is large: as an example, ε_0 can be as low as 0.2 provided K_A is 50 or higher.

From Fig. 1, it can also be observed how, as long as thermal transfer is concerned, the conditions of heat sink tending to black body behaviour and of $K_A >> 1$ coincide.

This plot can be divided in three distinct areas. The area below the curve $K_A = 1$ represents the Q^*_{CR} values which are not critical for any geometrical configuration. The area above $K_A \to \infty$ represents the specific power values which will cause ferrite to overheat for any geometry; while the influence of power values in the middle area is dependent on the specific ratio K_A.

The plots obtainable from Eq. 2 are thus a powerful tool in the early stages of design: they allow to define, for any given ferrite absorber and as a function of heat sink emissivity, whether the input RF power can be safely absorbed by the ferrite tiles without reaching T_C or if RF issues will arise. This evaluation can be done regardless of most geometrical considerations (including the value of K_A).

Assuming a 'minimum safe design' heat sink emissivity is ensured (e.g. 0.2), specific heat loads can be plotted as a function of ferrite temperature (Fig. 2). This plot can be very useful in the early phases of design to decide whether absorber radiation cooling is sufficient or active cooling (by conduction) should be sought.

If heat loads are estimated and ferrite maximum allowable temperature is known (based on Curie point or other considerations, such as compliance with UHV of outgassing rates), one may immediately conclude on the cooling method: if the working point lies above curve 1 (with $K_A \to \infty$) no geometrical configuration permits to evacuate given heat loads solely through radiation; conversely, it can be assumed that heat loads can be safely dissipated by radiation regardless of RF system geometry if one remains below curve 2 (obtained for $K_A = 1$). In intermediate cases, further system analyses are required.

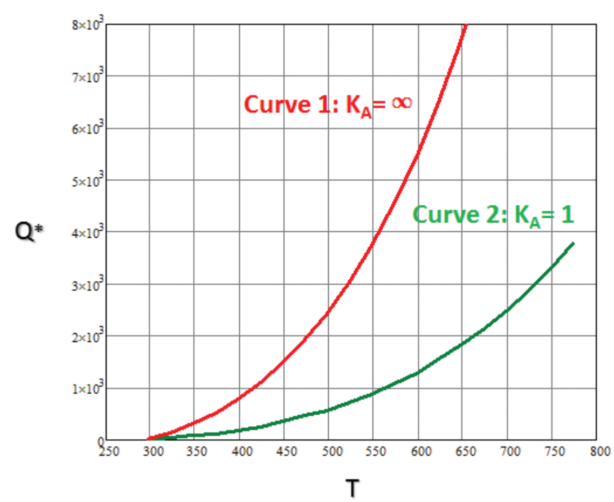

Figure 2: Q^* [W/m²] vs. ferrite Temperature [K] (ε_0=0.2).

CASE OF LHC TERTIARY COLLIMATOR (TCTP)

The TCTP is a tertiary collimator to be installed during LS1, embedding Beam Position Monitor (BPM) pick-ups to drastically reduce time for jaw alignment [4]. Fig. 3 shows a view of a TCTP jaw with 18 rectangular ferrite tiles (TT2-111R) lying on top of it.

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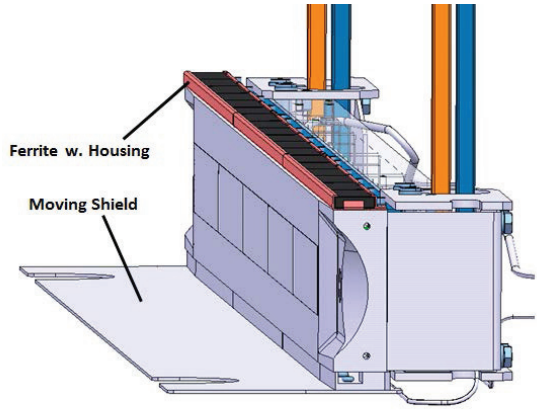

Figure 3: Assembled TCTP jaw.

In order to prevent the aforementioned brittleness issues, tiles are simply kept in position by their housing, without any clamping force. The only contact pressure between absorber and support is that provided by ferrite tiles deadweight.

As far as the system configuration is concerned, practically 100% of the surfaces viewed by ferrite are constituted by the housing and the shield on the opposite jaw, both in stainless steel and with $\varepsilon_0 \approx 0.3$. The steel components are directly screwed to the actively-cooled parts and, as a first approximation, can be considered at 295K.

$$h = 1.55K_1(\frac{\sqrt{2}p}{K_2}) \qquad [W/m^2K] \qquad (3)$$

where K_1, K_2: material properties coefficients

If one uses an elastic model [5] to estimate the thermal contact conductance (Eq. 3) and compares the resulting heat exchange with that transferred by radiation (with ferrite at the critical temperature of 648K), it can be seen that only around 1% of heat is actually exchanged by conduction. This validates the assumption of radiation as the only relevant heat transfer mechanism.

For the condition under study – which relies entirely on radiation with $K_A = 1.6$ – Fig. 1 provides a value of 3600 W/m^2 as the maximum allowable specific heat to be evacuated before ferrite reaches Curie point. This translates into a total power of around 440W for the two rows of ferrites.

It is interesting to determine the additional heat that would be evacuated by a TCTP if a very large K_A ($\rightarrow \infty$) is achieved; in such case the total power transferred by radiation would be 936 W, i.e. roughly 500 W more.

By coupling Eq. 2 with a normalized version of Eq. 3, one can estimate that the contact pressure required to evacuate by conduction the same additional heat load (500W) is only equal to 0.1 MPa.

It can thus be shown how conduction given by a low value of compression is as effective as trying to transform the surrounding heat sink into a black body (equivalent, as seen, to a great increment of K_A). This shows how, in case conduction can be safely guaranteed, it should be the option of choice, as its effectiveness in keeping ferrite cool is much higher than that of radiation.

CONCLUSIONS

With the recent increase of LHC luminosity and the observed overheating in several components embedding ferrite absorbers, it was felt that a simple tool for a preliminary assessment of ferrite heat transfer performance was desirable. Due to the poor mechanical properties of ferrite, the only heat transfer mechanism one can usually rely on is radiation.

A few guidelines and a figure of merit have thus been defined; the latter only depends on material properties and heat exchanging surfaces, regardless of all other geometrical parameters.

It has been found that for small ratios between the area of the heat sink and that of the ferrite absorbers, high values of emissivity should be sought. On the other hand, as this ratio grows, lower values of heat sink emissivity can be accepted, since the behaviour is tending to that of a black body enclosure.

A few plots are proposed; these depend only on basic parameters and can thus be efficiently used from the early stages of conception, allowing to timely orient the design of RF systems.

The case of the BPM-embedded LHC tertiary collimator (TCTP) has been analysed, showing that main assumptions can be related to real design cases.

ACKNOWLEDGMENTS

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