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METAMATERIAL ABSORBERS FOR BEAM-COUPLING IMPEDANCE MITIGATION

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Abstract

Charged particle bunches traversing cavity-like discontinuities in the beam pipe at relativistic velocities excite electromagnetic resonant modes that can detrimentally affect the dynamics of trailing bunches. This beam-cavity interaction, characterized in the frequency domain through the concept of beam-coupling impedance, poses significant challenges for beam stability and performance in high-energy particle accelerators. While conventional mitigation strategies encompass higher-order mode (HOM) couplers and lossy ferrite insertions, novel approaches leveraging metamaterial properties offer promising alternatives for selective mode damping. This investigation explores advanced metamaterial-based structures designed to specifically target and attenuate higher-order modes, thereby selectively reducing the beam-coupling impedance resonances.

INTRODUCTION

Metamaterials have revolutionized wave manipulation in several fields, including microwave and optical invisibility cloaking, miniaturized antennas, and perfect RF wave absorbers, among others. The capacity they have to modify the electromagnetic response of matter allows design options that were previously challenging or unattainable with conventional materials.

In particle accelerators, charged particles moving at relativistic speeds experience geometric wake fields due to their passage through geometrically non-uniform sections of the beam pipe such as accelerating cavities, diagnostic components, or transition pieces. These wake fields are electromagnetic (EM) fields generated by the particle bunches themselves as they traverse the discontinuities. In particular, the fields carried by the particle bunch can excite EM resonances in the structures, particularly when those structures function ”parasitically” as cavities [1]. These trapped resonant modes pose significant challenges, as they can endure across several bunch passes, leading to beam instabilities and energy dissipation. In circular machines, to account for wake fields in the frequency domain, the formalism of beam-coupling impedance can be adopted. The impedance of resonances can be described by the following analytical model [2]:

$$Z(\omega) = \frac{R_s}{1 + jQ(\frac{\omega}{\omega_R} - \frac{\omega_R}{\omega})}, \quad (1)$$

where R_s is the shunt impedance [3], Q is the quality factor and ω_R is the angular resonant frequency. Typically, unwanted resonances are mitigated using higher-order mode (HOM) couplers and/or through the inclusion of absorbing materials (such as ferrites) [4]. These solutions can be expensive and bulky. Furthermore, the inclusion of HOM couplers must be pondered already during the design process. In Ref. [5], it was suggested that the HOM modes could be attenuated through the strategic placement of metamaterials within the resonant-like structure. However, a quantitative evaluation of their impact on beam-coupling impedance reduction was not provided. In this paper, we begin by introducing metamaterials and, more specifically, a class of magnetic metamaterials designed to exhibit a resonant behavior at microwave frequencies. Their frequency-selective absorption properties are first characterized in simulation and then experimentally. Following this, we integrate these metamaterials into a custom-designed pillbox cavity that mimics typical resonant structures found in accelerator environments. Using both numerical simulations and experimental measurements, we show the effect of insertion of metamaterials that significantly suppress the resonant impedance of the cavity.

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METAMATERIALS

According to the definition in Ref. [6], electromagnetic metamaterials are artificial effectively homogeneous electromagnetic structures with unusual properties that are not readily available in nature. They consist, in practice, of a periodic arrangement of resonant elements. Each of these elements is often referred to as a meta-atom or unit cell, employing the same terminology used in solid-state physics for conventional materials. The property of effective homogeneity means the average structural dimensions of the meta-atoms are significantly smaller than the wavelength of the external driving field. This condition allows:

- Having refractive phenomena dominating over scattering or diffraction.
- Modelling the ensemble of meta-atoms using a complex susceptibility model considering effective medium parameters such as relative electric permittivity (ε) and magnetic permeability (μ).

The basic idea of metamaterials is that they have the ability to exhibit tailored resonant behavior at frequencies considerably lower than those of conventional materials. In traditional materials, electromagnetic resonances linked to atomic or molecule dipoles occur at optical or infrared frequencies due to the small size of the elements. In contrast, metamaterials achieve engineered resonances through the

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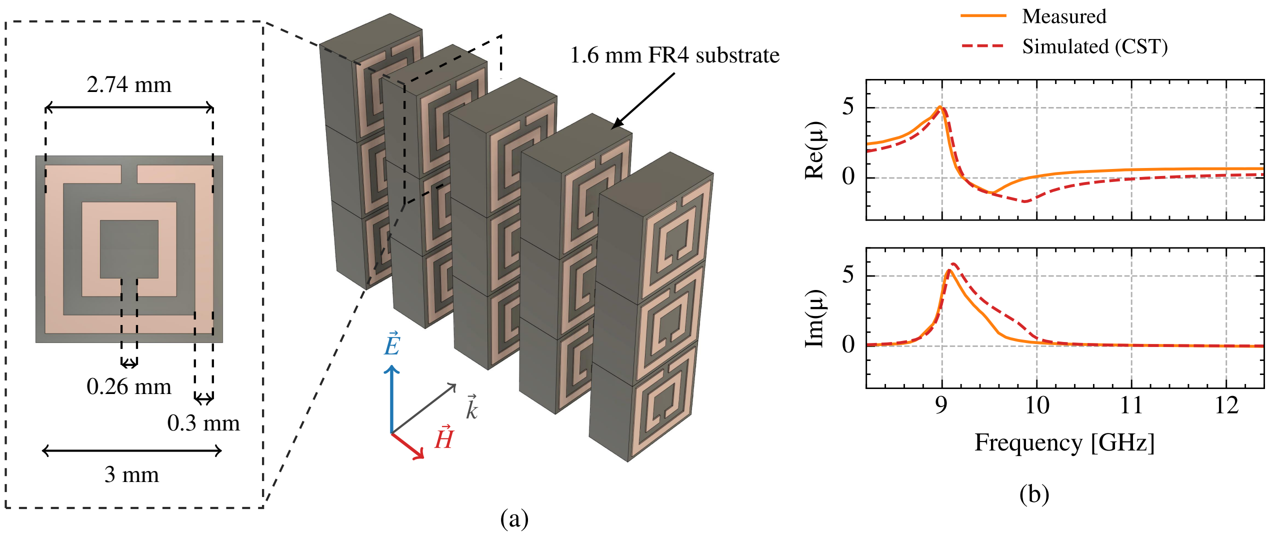

Figure 1: Metamaterial periodic structure based on metallic ECSRR on a dielectric substrate. On the left side dimensions of the ECSRR are reported. On the right side the extracted μ (for the shown EM field incidence) both from simulations (dashed red curves) and waveguide-based measurements (solid orange curves).

deliberate design of their meta-atoms, which are much larger than natural atoms but still sub-wavelength in scale. These resonant elements can be designed to interact strongly with electromagnetic waves at microwave or even lower frequencies. This capability derives from their geometric configuration rather than their inherent material composition: the resonant behavior is determined by circuit-like features (capacitive and inductive effects) which are inherently resonant and sub-wavelength. This allows to employ printed circuit design techniques and production technologies to engineer the capacitative and inductive effects as desired.

An example metamaterial unit cell is the edge-coupled split ring resonator (ECSRR), seen on the left side of Fig. 1. A practically easy to produce and relatively inexpensive realization of this structure is made of dielectric substrate with metallic traces (usually a 35 µm copper foil). An impinging magnetic field polarized perpendicular to the plane of the rings will induce currents in the metal traces, therefore generating a magnetic dipole in the same direction. The presence of two coupled split lines gives capacitative and inductive effects, allowing the circuit to resonate in a variety of frequency ranges (from hundreds of MHz to hundreds of GHz).

A periodic configuration of this structure may be regarded as an equivalent material, and its electromagnetic properties can be determined using standard parameter extraction techniques such as the Nicolson–Ross–Weir method [7]. Having a transverse magnetic (TM) plane wave impinging normally on the metamaterial lattice (as shown in Fig. 1(a)), the structure response in terms of magnetic permeability in the $\vec{H}$ field direction is reported in Fig. 1(b). Here, the real and imaginary parts of the magnetic permeability are reported as a function of frequency. The structure was designed to exhibit magnetic resonance at around 9 GHz, which is experimentally verified by Vector Network Analyser (VNA) measurements in a WR90 waveguide, demonstrating good agreement with simulation models. It should also be considered that the material shown is strongly bi-anisotropic. For the purposes of this investigation, the assumption of isotropy suffices.

IMPACT OF METAMATERIAL INSERTIONS ON BEAM-COUPLING IMPEDANCE

The magnetic resonant response of the material depicted in Fig. 1(b) shows two characteristic features:

1. There is a range of frequencies in which the effective material shows a negative real part of μ.
2. There is a range of frequencies where the imaginary part of μ shows significant positive values.

This last feature indicates significant selective absorption at the frequency of resonance. This suggests that such a structure may be utilized for the absorption of unwanted EM fields in a resonant structure.

To evaluate the impact in terms of beam-coupling impedance of metamaterial insertions in an accelerator device, an openable aluminum pillbox cavity was designed and manufactured (shown on the left side of Fig. 2). The cavity was designed to have the fundamental TM010 mode at 2 GHz and the first HOM (the deflecting mode TM110) at 3 GHz. This study focuses solely on the fundamental mode to show and prove the damping effect on longitudinal beam-coupling impedance. Finally, two ECSRR-based metamaterial slabs were designed and fabricated using CNC

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milling processes on RO3010 substrate to achieve resonance at 2 GHz. The slabs are intended to be positioned in a region of intense magnetic field perpendicular to the rings to maximize the coupling. The chosen locations are depicted on the right side of Fig. 2. Longitudinal beam-coupling impedance simulations of the empty structure were performed with both the CST Wakefield and Eigenmode solvers. Measurements were performed with a perturbation method (bead pull [8]), allowing to completely and accurately characterize the longitudinal impedance of the mode. The results obtained for the real part of the longitudinal beam-coupling impedance are shown in the left plot of Fig. 3 showing very good agreement.

The right plot of Fig. 3 shows the same comparison for the cavity loaded with metamaterial slabs, as depicted in Fig. 2. The simulations again show very good agreement, and the measurements also align satisfactorily, considering the uncertainties in reproducing the exact slab placement inside the cavity.

Overall, a reduction of more than an order of magnitude in the shunt impedance value is observed, along with a significant decrease in the Q factor. Additionally, a characteristic mode splitting is visible, resulting from the coupling between the cavity's resonant mode and the metamaterial resonance.

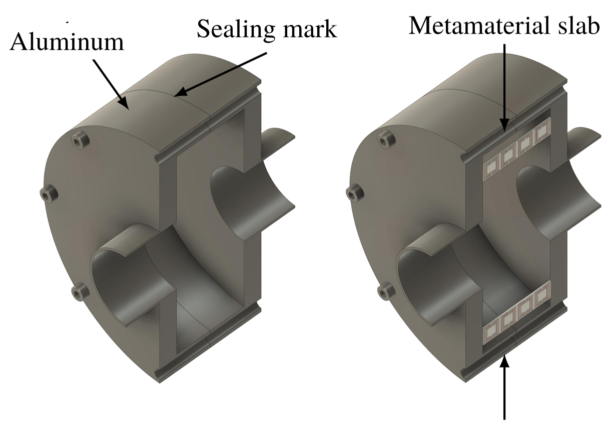

Figure 2: 3D CAD model of the pillbox cavity that was designed and produced for this study. On the left side a cut view of the empty structure. On the right side a cut view of the structure with two MTM insertions in the vertical plane. The cavity electrical conductivity was measured showing average values of 20.3 MS/m. The roughness given by the production methodology is around 0.8 µm rms. The cavity radius is 58.5 mm, the cavity length is 40 mm, beam pipe radius is 20 mm.

CONCLUSION

This study demonstrates the effectiveness of metamaterial-based absorbers for beam-coupling impedance mitigation in accelerator structures. The edge-coupled split ring resonator metamaterial, engineered to resonate at 2 GHz, was effectively inserted into a pillbox cavity, yielding almost an order of magnitude reduction in the longitudinal impedance peak and a significant decrease in the Q factor. The strong correlation between simulations and experimental measurements substantiates both the metamaterial characterization method and the impedance reduction strategy. Several intriguing research directions arise for future effort. Initially, expanding this study to examine the influence of metamaterial structures on transverse modes would yield a more comprehensive knowledge of their mitigation efficacy across every relevant impedance components. Moreover, additional investigation into the selectivity of various metamaterial structures might enable more accurate targeting of certain higher-order modes. The compact and cost-effective nature of metamaterial absorbers, combined with their proven effectiveness in impedance reduction, positions this technology as a promising alternative or complement to conventional impedance mitigation strategies in future accelerator designs.

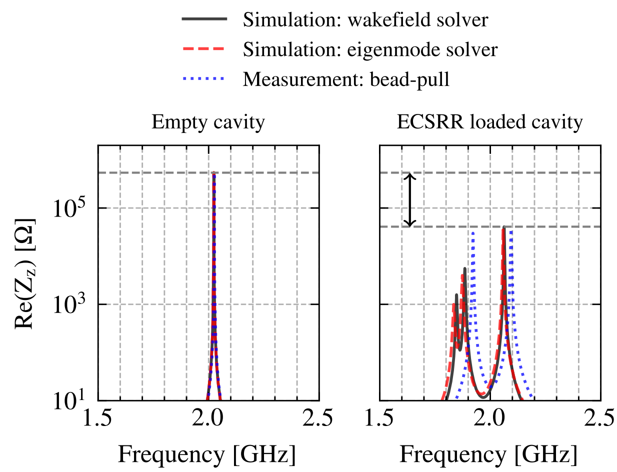

Figure 3: Real part of the longitudinal beam coupling impedance of the pillbox cavity shown in Fig. 2. The comparison between simulations and measurements both for the empty and metamaterial-loaded cavity are shown. It is possible to appreciate the reduction of more than one order of magnitude of the impedance peak when loading the cavity with metamaterial absorbers.

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