DEVELOPMENT OF METAMATERIALS FOR CHERENKOV RADIATION BASED PARTICLE DETECTORS

S. Antipov, W. Gai, W, Liu, J. G. Power ANL, Argonne, IL, 60439, USA
A.V. Tyukhtin, St. Petersburg State University, St. Petersburg, 198504, Russia
G. Semouchkin, E. Semouchkina Penn State University, University Park, PA, 16802, USA
A. Kanareykin, P. Schoessow Euclid TechLabs LLC, Solon, OH, 44139 USA

Abstract

Metamaterials (MTMs) are periodic artificially constructed electromagnetic structures. The periodicity of the MTM is much smaller than the wavelength of the radiation being transported. With this condition satisfied, MTMs can be assigned an effective permittivity and permeability. Areas of possible application of MTMs in accelerator science are Cherenkov detectors and wakefield devices. MTMs can be designed to be anisotropic and dispersive. The combination of engineered anisotropy and dispersion can produce a Cherenkov radiation spectrum with a different dependence on particle energy than conventional materials. This can be a basis for novel non-invasive beam energy measurements. We report on progress in the development of these media for a proof-of-principle demonstration of a metamaterial-based beam diagnostic.

INTRODUCTION

Metamaterials (MTMs) are artificial periodic structures made of small elements and designed to achieve specific electromagnetic properties. As long as the periodicity and the size of the elements are much smaller than the wavelength of interest, an artificial structure can be described by an effective permittivity ε and permeability μ, just like natural materials [1-5]. Waveguides loaded with metamaterials are of interest because metamaterials can change the dispersion relation of the modes in a waveguide significantly [10, 11]. Slow backward waves for example can be produced in a MTM-loaded waveguide without corrugations. Metamaterials can be designed to have particular anisotropy and dispersion characteristics. Therefore metamaterials can in principle be custom made for a particular application.

We are focused on the development of a detector based on Cherenkov radiation (CR) in a dispersive, anisotropic media that can be realized with MTMs. Cherenkov radiation in dispersive media differs significantly from the same effect in conventional detector media, like gases or aerogel [7-10]. Resonant dispersion can yield large refractive indexes. The radiation pattern of CR in resonant dispersive media presents lobes at very large angles with respect to particle motion [7]. Moreover, one can expect more energy radiated in some frequency bands, stronger particle energy dependence than for linear isotropic media, and the absence of a velocity threshold. In addition, an inversely directed cone of radiation and omnidirectional radiation are predicted for specific particle energies. Therefore the use of dispersive media with these new properties offers the possibility of improved Cherenkov detectors for both single particle detection and beam diagnostics.

The ability to tailor the properties of the medium to the application is especially attractive. Development of MTMs that exhibit Cherenkov radiation with unusual properties, for example, could form the basis for an improved practical Cherenkov detector. In addition, expected inverse Cherenkov radiation could be used for backfire antenna design [6] and also for the development of THz radiation sources.

This paper focuses on a particular feature of the concept of using artificial dispersive medium for detector applications: the response of MTM-Cherenkov devices to the energy of charged particles. In particular, the ability to measure low energy particles like protons or ions from e.g. laser spallation experiments [13] provides a potential application for this technology.

WAVEGUIDE WITH A THIN LAYER OF DIELECTRIC FOR LOW ENERGY PROTON DETECTION

Thin layer dielectric wakefield devices can be of use as diagnostics of low energy proton beams. The rest mass of a proton is almost 2000 times greater than rest mass of the electron. Even the low beta protons (~0.5·c) have relatively high energies. Hence the use of a magnetic spectrometer is problematic. A non-invasive wakefield technique can be of great help. The particle energy can be obtained from the spectrum of the radiated wakefield.

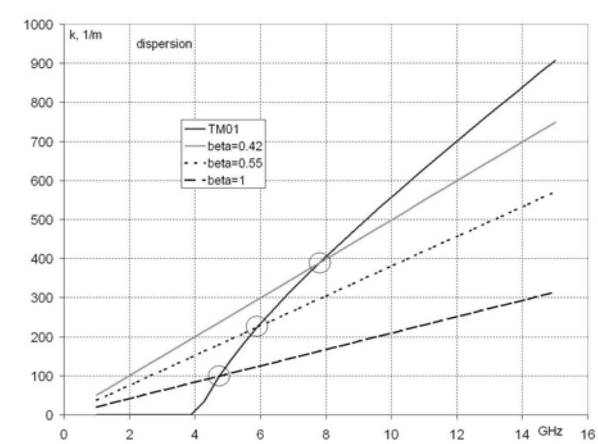

Figure 1: Dispersion of a low beta particles and the TM_{01} mode of the dielectric loaded waveguide.

Dispersion in a waveguide loaded with a dielectric tube can be easily calculated. Points of intersection between the mode dispersion curve and dispersion curves of particles of various energies correspond to the wakefield spectrum peaks (see Fig. 1). Direct wakefield simulation confirms that spectrum depends on particle energy for low beta particles. We simulated a 3mm sigma, 1nC beam with various gammas with the results shown in Figure 2.

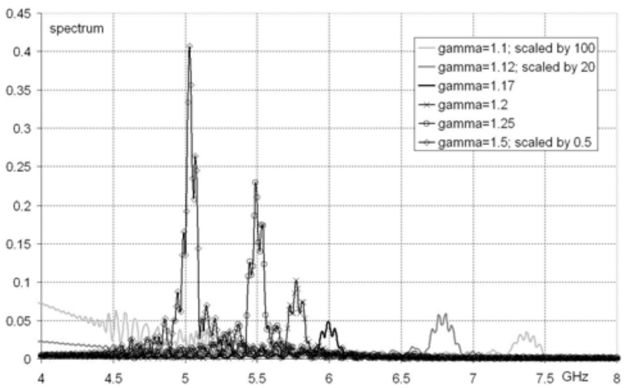

Figure 2: Wakefield spectrum simulation in the thin layer dielectric structure (alumina tube (ε = 9.4). OD = 40 mm, ID = 30 mm) showing the TM_{01} mode frequency shift as a function of γ.

WAKEFIELD GENERATION IN A WAVEGUIDE LOADED WITH THIN LAYER MTM

It will be practically impossible to use just the dielectric layer in a way described above for particles with high beta (electrons). To obtain the sensitivity the layer has to become extremely thin. At the same time the signal level drops significantly for thin layer structures. Resonant metamaterial elements can improve the situation.

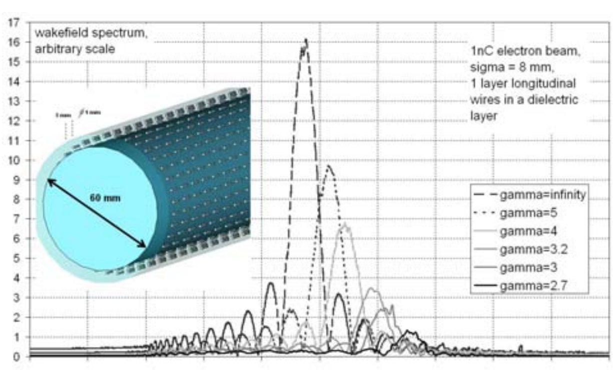

Figure 3: γ dependence of the wakefield spectrum for the thin layer composite wire-dielectric waveguide. Both the shift of the frequency of the fundamental mode and its intensity are sensitive to γ.

A single layer structure made of longitudinal wires is easy to design reliably and manufacture. Our simulations show that the wakefield spectrum depends on the beam energy more sensitively than through the β dependence of Cherenkov radiation in isotropic nondispersive dielectrics. Hence such a structure has the potential to be used for non-invasive energy detection.

As an example we considered the structure shown in Fig. 3. A single layer of short conducting wires parallel to the beam axis (z-direction) are embedded in a layer of low permittivity dielectric. The wire array introduces a resonant permittivity into the system as well as creating an anisotropic dielectric [5].

$$\varepsilon_{\parallel} = \varepsilon_{c\parallel} - \frac{\omega_{p\parallel}^2}{\omega^2 + 2i\omega_{d\parallel}\omega - \omega_{r\parallel}^2}, \quad \varepsilon_{\perp} = const \qquad (1)$$

The thin layer metamaterial is minimally disruptive to the beam; the wakefield is comparable to the beam self field (see Fig. 4). The beam induces currents in the wires, and the network of wires acts as a large LC circuit (self inductances of wires and capacitive gaps between the wires). This circuit produces an effective medium response to the wake.

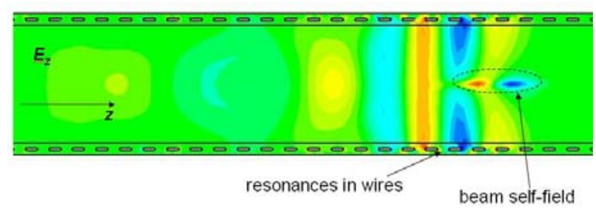

Figure 4: Simulation of axial electric field of an 8mm 1nC electron beam passing through the dielectric/single wire layer structure.

Metamaterials are complex structures. One of the critical issues with metamaterials is how well the particular metamaterial approximates an effective medium. A metamaterial layer has to be assigned some effective thickness to define its effective medium parameters.

For the theoretical model [12] we estimated the resonant frequency to be 24.5 GHz and plasma frequency to be 22 GHz. The theoretical model agrees well with the simulation.

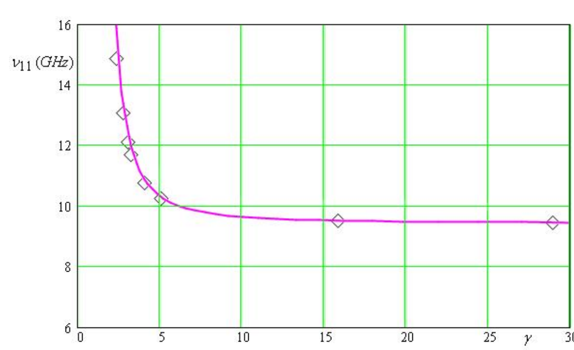

Figure 5: Mode frequency ν_{11} as a function of the Lorentz factor. The diamonds show the simulation results. The magenta line is the theoretical curve for anisotropic resonant medium layer with an adjusted plasma frequency $\omega_{p\parallel}$ = 22 GHz.

The effect of the wakefield spectrum's strong dependence on the particle energy does not have to rely on effective parameters of the metamaterial being negative. The key property here is dispersion of a particular kind - a monotonic decrease in permittivity (ε) with rising frequency in a certain frequency range. Similar condition can be realized with Debye-type dispersion.

OVERVIEW OF LOW TEMPERATURE COFIRED CERAMICS TECHNOLOGY FOR MTM FABRICATION

Metallic metamaterial structures have some limitations due to spatial anisotropy [14] and are more sensitive to manufacturing tolerances then dielectric metamaterials. We are looking into dielectric metamaterials for further studies eventually leading to a beam test. Such designs can be produced by the low temperature co-fired ceramics (LTCC) method [15]. Low-temperature co-fired ceramic material systems are used to fabricate a variety of mesoscale devices with diverse functions, and have particular advantages for developing dielectric metamaterials and PBG structures. Cylindrical resonators are punched from a laminated stack of Bismuth-Zinc-Tantalate (ε=62). The resonators are placed into a low temperature cofired ceramic (LTCC) tape (ε=7.8) and fired to 875˚ C (see Fig. 6).

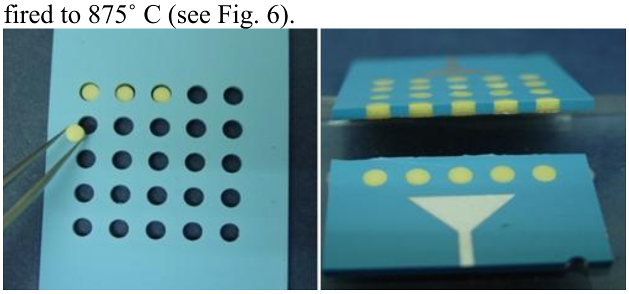

Figure 6: LTCC manufacturing of a dielectric metamaterial. Left: before firing. Right: after firing to 875˚ C. The matrix shrinks around the resonators.

Similar to cut wire based resonators cylindrical dielectric resonators are capable of supporting electric resonance and are also capable of supporting magnetic resonance. By choosing the direction of the dielectric cylinder axis one can control the strength of the magnetic effects.

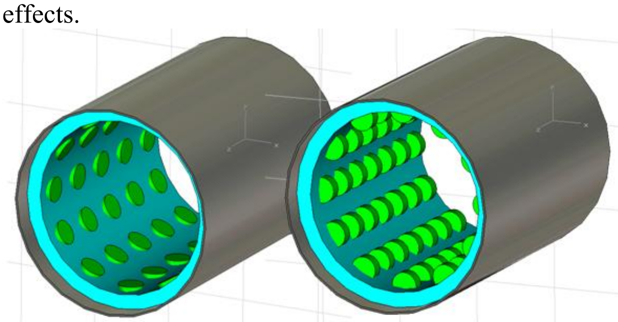

Figure 7: Thin layer dielectric metamaterial geometries under investigation.

Some structures under the investigation with low magnetic effects for the TM_{01} mode are shown in Fig 7. Structures with strong magnetic resonances are also being considered.

SUMMARY

We discussed wakefield generation in metamaterial loaded waveguides. We showed that for low beta particles their energy can be determined from the wakefield spectrum produced in a simple waveguide loaded with a thin layer dielectric liner. With the help of a thin metamaterial layer the wakefield spectrum sensitivity can be extended to higher energies.

An engineered dispersive medium can be designed and tuned to provide wakefield sensitivity to particular gamma regions. We are investigating several dielectric metamaterial designs to achieve good sensitivity combined with simplicity of fabrication and vacuum compatibility for beam experiments.

AKNOWLEDGEMENTS

Authors would like to thank Slava Yakovlev (FNAL) for the help with simulations. The submitted paper has been created by UChicago Argonne, LLC, Operator of Argonne National Laboratory ("Argonne"). Argonne, a U.S. Department of Energy Office of Science laboratory, is operated under Contract No. DE-AC02-06CH11357. The work is also supported by DOE grant #DE-FG02-08ER85031

REFERENCES

[1] J. B. Pendry, A. J. Holden, W. J. Stewart, and I. Youngs, Phys. Rev. Lett. 76, 4773 (1996).
[2] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, IEEE Trans. MW Theory Tech. 47, 2075 (1999).
[3] R. Shelby, D. R. Smith, and S. Schultz, Science 292, 77 (2001).
[4] D. R. Smith, et al., Phys. Rev. Lett. 84, 4184 (2000).
[5] R. W. Ziolkowski IEEE Trans. Antennas and Propagation, 51, 7, 2003.
[6] A. Grbic and G. V. Eleftheriades, J. Appl. Phys. 92, 5930 (2002).
[7] J. Lu, et al, Opt. Express 11, 723 (2003).
[8]Yu. Averkov, V. Yakovenko, PRB 72, 205110 (2005).
[9] A. V. Tyukhtin, S. P. Antipov, A. Kanareykin, and P. Schoessow, IEEE Proc. PAC 2007 pp. 4156–4158.
[10] S. Antipov, et al., J. Appl. Phys. 102, 034906 (2007).
[11] S. Antipov, et al. J. Appl. Phys. 104, 014901 (2008).
[12] A. V. Tyukhtin, S. P. Antipov, A. Kanareykin, and P. Schoessow, these Proceedings.
[13] I.Pogorelsky et al., Proc. AAC 2008, AIP CP 1086, 2009 pp.532-537.
[14] P.A. Belov, et al, Phys. Rev. B, v.67, 113103 (2003)
[15] A. Baker, M. Lanagan, C. Randall, E. Semouchkina, G. Semouchkin. Int. J. Appl. Ceram. Technol., 2 [6] 514–520 (2005).