OBSERVATION OF WAKEFIELDS IN A 17 GHz METALLIC PHOTONIC BANDGAP (PBG) STRUCTURE*

R. A. Marsh†, M. A. Shapiro, R. J. Temkin
Plasma Science and Fusion Center, MIT, Cambridge, MA 02139, USA
E. I. Smirnova, LANL, Los Alamos, NM 87545, USA

Abstract

Preliminary results are reported on experimental wakefield measurements made on a 6 cell, 17.14 GHz metallic photonic band gap (PBG) accelerator structure. Wakefields were observed using a variety of detectors and methods. The PBG structure is open, containing no outer wall, and radiation has been observed through a window in the surrounding vacuum vessel. The output coupler port has also been used with a vacuum window to observe radiation coupling out of the port. Estimations of radiation are made using HFSS and basic wakefield theory. Measurements have been made using video diode detectors and a heterodyne receiver. Plans are discussed for further experiments.

INTRODUCTION

Wakefields are a serious concern for future accelerators, and the structures that will be used to build them. Scaling with frequency squared, wakefields must be even more carefully dealt with at higher frequency operation. Higher order mode damping, as well as cavity detuning are two tools used to mitigate the deleterious effects of wakefields in accelerator structures. Another idea, that has been demonstrated recently is the use of a photonic band gap (PBG) accelerator structure [1, 2]. Rather than a pillbox form, the cavity is a periodic lattice with a defect. The periodic structure forms a photonic crystal, which has frequency dependent transmission properties. Ideally, an operating mode is confined within a gap in which no propagating solution to the dispersion equation can be found; whereas higher order modes propagate out of the structure. Higher order modes in such a structure are no longer localized near the beam holes, and so couple more weakly from cell to cell, or to the beam. Acceleration with such a structure has been demonstrated, but the observation of the wakefields in the structure, or the amount of damping it provides have not been studied. In this paper preliminary results are reported on work to directly observe wakefields in a 6 cell metallic PBG accelerator structure.

PBG Accelerator Structure

Design, cold test, and demonstrated acceleration using this electroformed metallic PBG structure are reported in [1, 2]. The structure is a triangular lattice of metallic rods, supported by standard pillbox-like washers. A single rod is removed from the center of the lattice to form the defect. Three rows of rods are used to confine the TM_{01}-like operating mode. An HFSS simulation showing this operating mode is shown in Fig. 1. A summary of design parameters is shown in Table 1.

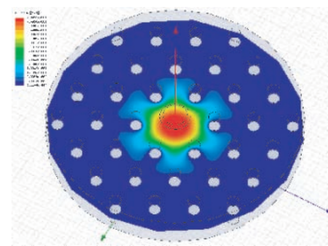

Figure 1: HFSS simulation results showing the electric field magnitude of the TM_{01}-like fundamental operating mode of the PBG accelerator structure. Simulation parameters are as listed in Table 1.

Table 1: Dimensions and design properties of the PBG accelerator structure

Rod radius	1.04 mm
Rod spacing	6.97 mm
Cavity length	5.83 mm
Iris radius	2.16 mm
Iris thickness	1.14 mm
TM_{01}-like mode	17.140 GHz
Group velocity	0.013c
Gradient	$25.2\sqrt{P[MW]}$ MV/m

THEORY

Wakefield theory can be developed as an expansion of cavity eigenmodes with varying coupling to the beam. In an ideal accelerator structure the beam couples very strongly to the operating mode, and very weakly to any higher order modes. Other work in this conference [3] explores cavity modes as they appear in PBG structures. Using HFSS simulations, the frequency, cavity quality factor, and loss factors for various modes are calculated. These are used with the following relations to arrive at the power lost by a charge into the n^{th} mode as it passes through an unpowered structure [4].

$$k = \frac{V_b^2}{4U} = \frac{\omega}{4}\frac{R}{Q_0} \quad (1)$$

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† roark@mit.edu

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$$\Delta P_n = q^2 \frac{\omega_n k_n}{Q_{0n}} \tag{2}$$

The loss factors k [V/C] are calculated by Eq. 1 using the beam induced voltage V_b, and the cavity stored energy U. These can then be related to the cavity frequency ω, shunt impedance R, and unloaded quality factor Q_0. The general loss factor formulas can then be used to calculate the charge power loss [W] using Eq. 2 for each higher order mode n. Rather than a single bunch traversing the structure, there will be a train of bunches, some portion of which will add coherently. This is dependent on the group velocity of the mode and the length of the structure.

EXPERIMENTAL SETUP

Experiments were performed at the MIT high gradient acceleration lab, using the MIT Haimson Research Corporation 17 GHz linac. The beam parameters were as given in Table 2.

Table 2: Operating parameters

RF Frequency	17.14 GHz
Beam Energy	18 MeV
Bunch Length	1 ps
Bunch Charge	1-15 pC
Transverse Size	1.3 mm
Pulse Length	100 ns

The linac is powered by a single high power modulator [5], which powers both the linac DC thermionic gun, and a new high gain 17.14 GHz klystron [6]. Beam current and size are controlled by focusing the beam with solenoidal lenses before collimation. The DC beam is bunched prior to linac injection using an RF chopper and prebuncher system, operated to produce 1 ps bunches. The linac is a constant gradient $2\pi/3$ traveling-wave structure, providing a beam energy of 18 MeV. An RF pulse length of 100 ns corresponds to a bunch train of ∼40 ns, because of the 60 ns fill time of the accelerator structure. This beam was passed through the PBG structure and into a Faraday cup, where the current traversing the structure was measured. The 6 cell PBG structure is shown in Fig. 2. It is housed in a stainless vacuum can on the beam line, shown schematically in Fig. 3. A fused quartz window was installed on the bottom of the vacuum chamber housing the PBG structure, the bottom of Fig. 3, so that radiation could be observed leaking out of the open PBG structure. The input coupler, the top left waveguide section in Fig. 3 was shorted, and a window was installed on the output coupler, top right waveguide section in Fig. 3, so that observations could also be made of radiation coupling out of the structure via the output coupler port.

Two sets of diode detectors were used, at both Ku (12-18 GHz) and Ka (26-40 GHz) bands. They were calibrated using their respective power heads and meters. The horns, waveguide, adapters, attenuators and vacuum windows used were calibrated over their respective frequency ranges using an Agilent Precision Network Analyzer. A heterodyne receiver was used to look at the frequencies of the observed radiation. This heterodyne system consisted of a 8-18 GHz YIG local oscillator, and a 2-18 GHz double balanced mixer.

Figure 2: 6 cell metallic PBG accelerator structure

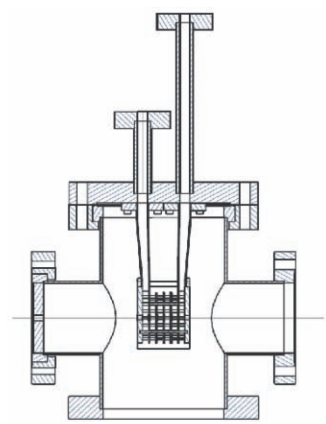

Figure 3: PBG accelerator structure vacuum vessel

EXPERIMENTAL RESULTS

Radiation was observed both exiting the output coupler port and the vacuum chamber window. From the HFSS calculated loss factor of $3.4 \cdot 10^{12}$ V/C, and using Eq. 2, an estimated 71 W of power is lost by the beam into the fundamental 17.14 GHz mode. For the first dipole mode at 23 GHz, a loss factor of $3.2 \cdot 10^{7}$ V/C is expected for an on axis beam, and $9.5 \cdot 10^{10}$ V/C, for a 1mm off axis beam. For the higher order modes, in general, milliwatts of power are expected. Power observations were of this order, with a summary of order of magnitude given in Table 3.

Radiation is expected to scale quadratically with bunch charge, as shown in Eq. 2. Wakefield scaling with current

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Table 3: Power levels of observed wakefields for the different band diodes and detector positions. These measurements were all made with 100 mA average current, or 5.8 pC/bunch

	Ku	Ka
Output coupler	24 W	45 mW
Vacuum chamber	1 mW	6 mW

was observed as the average current was varied from 20-250 mA, corresponding to a bunch charge in the range of 1-15 pC. Results for the Ka (26-40 GHz) band diode detector observing on the output coupler port are shown in Fig. 4. Good agreement is obtained with a quadratic fit, with error arising from both the statistical diode signal variation and shot to shot current fluctuation.

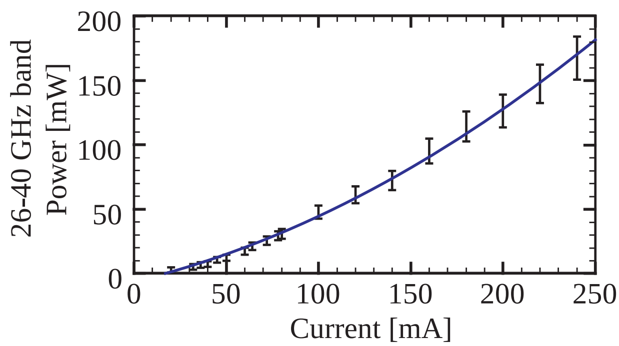

Figure 4: Scaling of power in Ka (26-40 GHz) band with current. Quadratic fit shown in blue with data given as black bars

Heterodyne frequency measurements were made, and peaks were only observed at integer multiples of the linac RF frequency, 17.14 GHz. A summary of observed frequencies is given in Table 3. No clear signal was observed of the expected higher order modes of the PBG structure, such as the 23 GHz dipole mode.

Table 4: Heterodyne receiver observations in GHz

Frequency	Multiple
17.14	1
34.28	2
51.42	3
68.56	4
85.7	5

Wakefield measurements were also made as the beam was injected off axis, in hopes of exciting higher order modes, and probing the position dependence of k_n. The 1.3 mm beam size, and 3.5 mm input collimator diameter give a reasonable range of position variation. Results proved to be dominantly influenced by beam current loss as the beam was intercepted by the collimator. Current transmitted through the structure varied as would be expected when a 1.3 mm gaussian profile is passed through a 3.5 mm aperture. After normalizing for beam current variations, the results of observations made with the Ku (12-18 GHz) band diode were unchanged as a function of beam offset in mm. As expected, the loss factor for the fundamental does not vary much with offset position. Observations in the Ka (26-40 GHz) band, similarly show only dependence on the total current through the structure, and little variation with beam offset alone.

DISCUSSION

Preliminary measurements show the order of magnitude wakefields expected. The power emitted at integer multiples of the RF frequency, 17.14 GHz is much greater than that emitted into the higher order modes of the structure. Using the heterodyne receiver, several weak signal groupings of peaks were observed in the range of 23-27 GHz, as expected for higher order modes of the structure. Filtering techniques and off axis injection will need to be optimized in future experiments in order to clearly observe these modes.

Future PBG structures will need to be designed with wakefield damping. The open nature of the PBG lattice makes this simple, but it is still necessary in order to decrease the unloaded Q of higher order modes to acceptable levels. Future experiments with this metallic PBG structure will provide a baseline level for wakefield damping performance, and indicate what level of improvement is necessary for competitive future structure designs. A longer metallic PBG structure is planned, of ∼20 cells, with a group velocity of between 0.03c and 0.05c. This PBG structure will be more sensitive to higher order mode wakefields, and demonstrate wakefield damping using a realistic accelerator structure.

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