OBSERVATION OF WAKEFIELDS IN A BEAM-DRIVEN PHOTONIC BAND GAP ACCELERATING STRUCTURE*

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Abstract

Wakefield excitation has been experimentally studied in a 3-cell X-band standing wave Photonic Band Gap (PBG) accelerating structure. Major monopole (TM_{01}- and TM_{02}-like) and dipole (TM_{11}- and TM_{12}-like) modes were indentified and characterized by precisely controlling the position of beam injection. The quality factor Q of the dipole modes was measured to be ~10 times smaller than that of the accelerating mode. A charge sweep, up to 80 nC, has been performed, equivalent to ~30 MV/m accelerating field on axis. A variable delay low charge witness bunch following a high charge drive bunch was used to calibrate the gradient in the PBG structure by measuring its maximum energy gain and loss. Experimental results agree well with numerical simulations.

MOTIVATION

Photonic Band Gap (PBG) structures for particle acceleration have been intensively investigated since the concept was introduced more than a decade ago [1]. Capability for single mode confinement makes these structures very attractive for the future particle accelerator designs which require severe transverse mode suppression [2]. However, wakefields, including the monopole and dipole modes generated in a PBG accelerating structure by a traversing beam have never been clearly characterized in a beam test. In general a PBG accelerating structure is constructed with a periodic array of metallic rods. Due to the periodicity of the structure, frequency bands (band gaps) exist through which it is forbidden for electromagnetic radiation to propagate. In order to allow particles to move through the structure, one rod is removed from the lattice to create a beam channel. This removal creates a defect in the "crystal" where the accelerating mode will be confined. The lattice parameters can be chosen in such a way that neither the transverse modes nor the high order monopole modes are confined in the beam channel. In the real structure, the number of rods is finite. This leads both to a decrease in the quality factor of the accelerating mode because of imperfect confinement in the channel and the possibility of trapping Higher Order Modes (HOMs). However, with a proper design, the quality factor of HOMs is, in general, significantly lower than that of the accelerating mode. In this article, we report on a successful wakefield characterization in a beam test of an X-band 3-cell PBG accelerating structure, in which the (fundamental and high order) monopole modes and dipole modes were profiled by precisely varying the beam offset relative to the nominal beam axis of the structure.

PBG STRUCTURE UNDER TEST

We designed an 11.424 GHz externally-powered travelling wave PBG accelerating structure using a two-dimensional triangular lattice of copper rods between two copper plates. The beam channel was formed by removing the center rod and drilling irises on the plates. The phase advance between every two plates is 120 degrees at 11.424 GHz, designed so that the fundamental mode is synchronous with an ultra-relativistic beam. The major design parameters of the structure are summarized in Table 1. Three cells have been prototyped using the electroforming technique. With the aim of experimentally studying the wakefield in the PBG structure, we assembled 3 PBG cells serving as a standing wave PBG structure (see Fig. 1). The fundamental monopole modes derived from the simulation are 11.1 GHz, 11.31 GHz, and 11.52 GHz, representing 0, $\pi/3$, and $2\pi/3$-like spatial modes, respectively. The frequency of each mode differs slightly from that in the travelling wave case because of the different boundary conditions. However, these deviations did not affect the goal of this investigation in terms of monopole/dipole mode identification and characterization.

Table 1: Designed parameters of the X-band travelling wave PBG accelerating structure

Geometric and accelerating parameters	Values
Rod Radius, *a*	1.64 mm
Spacing between rods, *b*	10.19 mm
Iris diameter	9.61 mm
Iris thickness	1.71 mm
Plate spacing	7.04 mm
Synchronized freq. of the accelerating mode	11.424 GHz ($2\pi/3$ mode)
Group velocity	0.05 c
Q	5461
r/Q	10.5 kΩ/m

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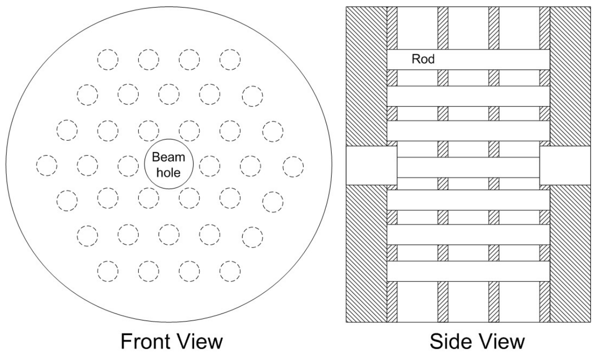


Figure 1: Schematic drawings of the 3-Cell standing wave PBG structure used in the beam test.

BEAM TEST

The wakefield experiment was performed at Argonne Wakefield Accelerator (AWA) facility located at Argonne National Laboratory (ANL), where a 1.3 GHz photoinjector can provide ~100 nC charge in single bunch operation or several tens of nC per bunch in bunch train operation (charge varies with the number of bunches per train) [3]. The energy of the electron bunch is boosted to ~14 MeV after one section of linac. The experimental setup is shown in Fig. 2. The PBG structure was mounted on a motorized actuator through a special fixture and housed inside a 6-way vacuum cross. An ultra high vacuum (UHV) compatible coaxial rf probe was used to monitor the wakefield signal excited by the electron bunch. The probe was mounted on a 1.33 inch bellows on one port of the cross so that the pin tip of the rf probe can be moved in and out the PBG lattice if necessary. The whole cross, together with the probe, was mounted on top of a stepping motor driven translation stage. Meanwhile, the cross was inserted into the AWA beamline through two 3-3/8 inch bellows on both ends, which was able to provide the mechanical flexibility for the cross to move a few mm transversely. This configuration would enable us

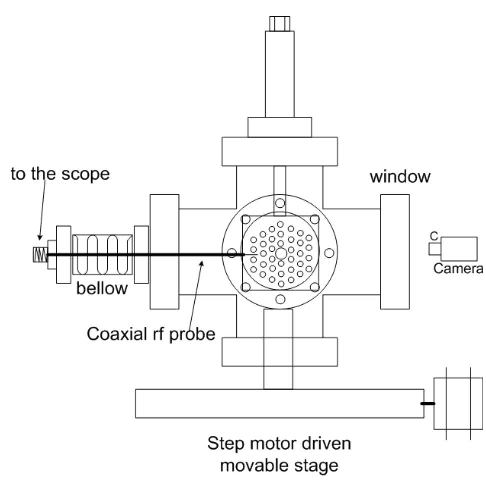


Figure 2: Experimental setup in the AWA beamline (front view).

to precisely control the beam offset in the PBG structure by remotely shifting the cross perpendicular to the beam axis via a stepping motor, ensuring that the position of the probe relative to the PBG structure was always fixed. Other diagnostics during the experiment included: 1) two Inductive Current Transformers (ICTs) on both sides of the 6-way cross to record the charge entering and exiting the structure; 2) phosphor screens on each side of the cross to monitor the transverse beam profile; 3) an energy spectrometer on the downstream end to measure the beam energy; 4) a CCD camera to detect any light from the possible rf breakdown of the PBG structure through the window on one port of the cross.

In the experiment, the rf signal of the excited wakefield in the PBG structure was captured by the probe and transmitted to a 16 GHz digital oscilloscope (50 Gs/s sampling rate). Figure 3 shows a typical signal generated by a low charge (~0.5 nC), short (~1.5 mm rms bunch length) off-axis electron bunch and its power spectrum. The simulation was performed using CST Particle Studio®. The lowest dipole mode (TM_{11}-like), has been identified at 14.46 GHz. The other significant modes shown in Fig.3 include a higher order monopole mode (TM_{02}) at 14.88 GHz; and three high order dipole modes (TM_{12}-like), at around 15.27 GHz. Note that, in the spectrum plot, all modes, except for the three fundamental monopole modes, have broader widths. This means that in the time domain, the signals decay much faster for HOMs than for the monopole modes, indicating that the Q for all HOMs is lower.

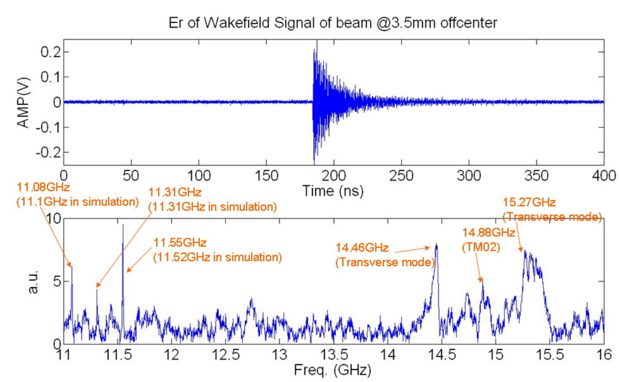


Figure 3: The typical wakefield signal from an off-axis bunch captured by the rf probe and its power spectrum.

Mathematically, we can obtain the Q of each mode by filtering them out in the frequency domain and transforming back to the time domain using the inverse FFT (IFFT), followed by performing a decay curve fitting of the signal envelope. We should point out that the accuracy of Q in this technique is limited by the frequency resolution of the signal and the mode spacing. In the experiment, the probe signals were recorded in a 400 ns time window, which gives us a 2.5 MHz frequency resolution. As an example, we calculated the Q of the $2\pi/3$ mode at 11.55 GHz to be ~1400 and ~170 for the Q of the dipole mode at 14.46 GHz. This successfuly demonstrates the intrinsic advantage of the PBG accelerating structure in terms of HOM suppression.

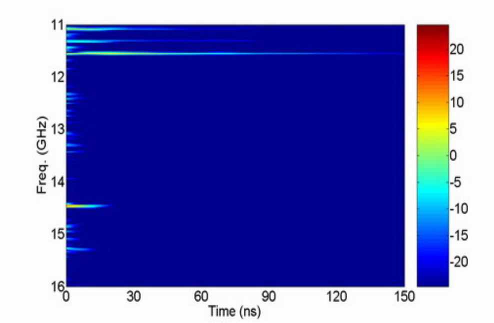
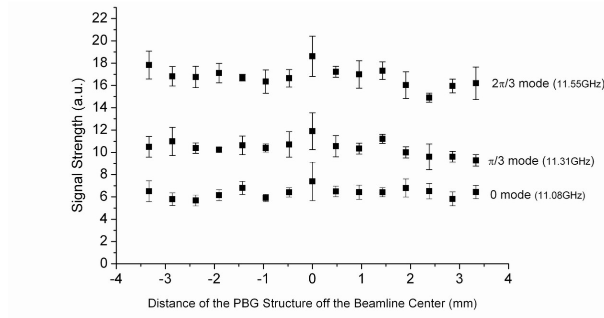


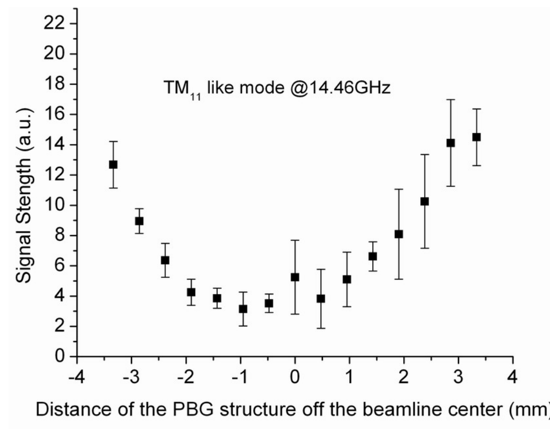
Figure 4: Time-Frequency analysis of the wakefield signal from an off-axis bunch captured by the rf probe.

Figure 4 shows the time-frequency representation of this probe signal captured when the beam is offset. The plot is generated by a Short-Time Fourier Transformation (STFT) that uses a 40 ns Hanning Window shifting by 1 ns per step. We can clearly see that the fundamental monopole mode, particularly the 2π/3 mode, oscillates for over 150 ns while the dipole modes die down in 20 ns.

In order to experimentally identify the major monopole and dipole modes using a different approach, we characterized the behavior of each mode by precisely controlling the electron bunch position across the beam iris of the PBG structure. This was implemented through the stepping motor-driven translation stage presented in Fig. 2. A single ~0.5 nC bunch was used to ensure that 100% of the beam passes through the PBG structure. We recorded the charge out of the structure and the probe signal simultaneously so that we could normalize the signal strength to the charge in the plots. Location of the minimum dipole signal, which represents the actual beam center, was slightly (<1 mm) away from the physical center of the beamline where we have indicated zero offset in the plots. The signal strength of the dipole modes was measured above zero because of the background noise. The measurement results are shown in Fig. 5. As expected, the signal strength of three fundamental monopole modes are independent of the beam offset (Fig. 5(a)); but that of the dipole modes shows a very strong dependence on transverse position (Fig. 5(b) and 5(c)).)



(a)



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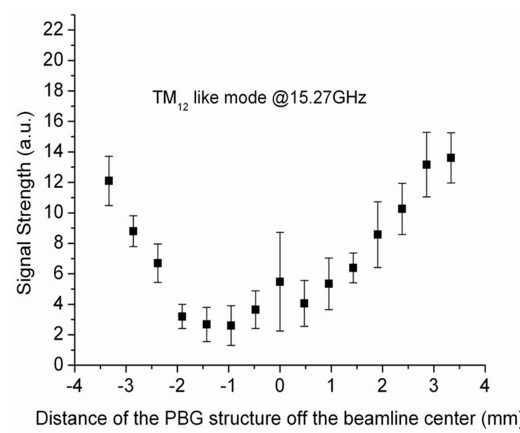

(c)

Figure 5: Measured signal strengths for 3 fundamental monopole (a) and two dipole modes (b) and (c) with varying beam offset.

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