

NOVEL METALLIC STRUCTURES FOR WAKEFIELD ACCELERATION

Xueying Lu, Michael A. Shapiro, Richard J. Temkin, MIT, Cambridge, MA 02139, USA

Abstract

Three novel ideas for wakefield acceleration (WFA) of electrons with metallic periodic subwavelength structures are presented. The first idea is a deep corrugation structure for collinear WFA. A nominal design for the Argonne Wakefield Accelerator (AWA) is shown. The second idea is an elliptical structure with two beam holes at the two focal points for two-beam acceleration (TBA). The third idea is a metamaterial (MTM) ‘wagon wheel’ structure designed as a power extractor at 11.7 GHz for the AWA. The fundamental mode is TM-like with a negative group velocity.

INTRODUCTION

Wakefield acceleration (WFA) is a concept to achieve high accelerating gradients by using a compact high-charge relativistic drive bunch to accelerate a following low-charge witness bunch. There have been studies in the plasma and dielectric WFA, and gradients of GV/m have been reached [1,2]. A metallic WFA structure may be attractive because it is stable and less susceptible to damage. In this paper, novel ideas of WFA using metallic structures are discussed, including the idea of a metamaterial (MTM) structure. MTMs are subwavelength periodic structures with novel electromagnetic features, like negative group velocity of the lowest mode. These features give rise to new properties in the interaction of the MTMs with an electron beam [3].

This paper presents sequentially three metallic structures, a cylindrical deep corrugation structure for collinear WFA, an elliptical structure for two-beam acceleration (TBA), and a wagon wheel MTM structure for power extraction.

DEEP CORRUGATION STRUCTURE

The deep corrugation structure is an array of metallic subwavelength cylindrical cavities, as in Fig. 1. It is different from the conventional corrugated waveguide structure in the way that the corrugation depth is larger than the iris radius, and the period is much smaller than the wavelength.

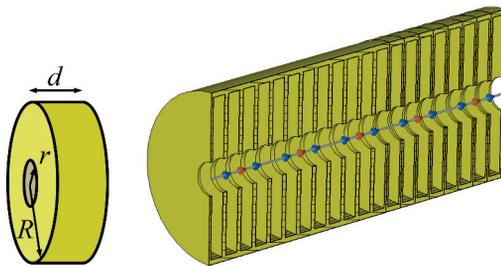


Figure 1: Deep corrugation structure. Left: a single cavity. Right: full multi-cell structure.

Two methods of analysis are adopted to study the wakefield in the structure excited by a short electron bunch. The

first one is the analytical method to calculate the wakefield in a single cavity, and the second one is the numerical method to simulate the wakefield in a multi-cell structure.

Analytical Wakefield Calculation of a Single Cell

The analytical model is a single cavity with radius R and length d excited by a point charge with charge Q traveling at velocity v_0 in the z direction. By solving the Maxwell equations in the cavity with the excitation current

$$J_z(\mathbf{r}, t) = \frac{Qv_0}{2\pi r} \delta(r) \delta(z - v_0 t), \quad (1)$$

we have,

$$E_z(r, z) = \sum_{s=1, n=0}^{\infty} \alpha_{s,n} \left(\frac{cp_s}{R} \right)^2 J_0 \left(p_s \frac{r}{R} \right) \cdot \cos \left(\frac{\pi n}{d} z \right) \left[(-1)^n \frac{\sin \left[\Omega_{s,n} \left(t - \frac{d}{v_0} \right) \right]}{\Omega_{s,n}} - \frac{\sin(\Omega_{s,n} t)}{\Omega_{s,n}} \right], \quad (2)$$

where p_s is the s^{th} zero of the J_0 function, and

$$\alpha_{s,n} = \frac{Qv_0}{\pi \epsilon_0 g_n d} \frac{1}{R^2 J_1^2(p_s)} \frac{1}{\Omega_{s,n}^2 - (\pi n v_0 / d)^2},$$

$$g_n = \begin{cases} 1, & \text{for } n = 0 \\ 0.5, & \text{otherwise} \end{cases},$$

$$\Omega_{s,n} = c \sqrt{\left(\frac{p_s}{R} \right)^2 + \left(\frac{\pi n}{d} \right)^2}.$$

When the excitation charge is changed to a Gaussian bunch with an rms length of σ_z , the wakefield $E_{z,g}$ is,

$$E_{z,g}(r, z) = \sum_{s=1, n=1}^{\infty} E_{s,n}(r, z, t, \Omega_{s,n}) \exp \left(-\frac{\Omega_{s,n}^2 \sigma_z^2}{2c^2} \right), \quad (3)$$

where $E_{s,n}(r, z, t, \Omega_{s,n})$ is the same as E_z in Eq. 2.

Numerical Simulation of a Multi-cell Structure

The CST Particle Studio Wakefield Solver is used to simulate the structure excited by a short relativistic bunch.

Fig. 2 shows the longitudinal electric field on the middle cutting plane with a bouncing pattern observed. The pattern is formed when the drive bunch initially excites a decelerating wake (in red) after it. The decelerating wake travels outward and bounces at the metal wall with a 180-degree phase shift, transforming to an accelerating wake (in blue). The accelerating wake then travels inward and is focused at the beam axis. A following witness bunch can be placed at the refocusing location in blue to be accelerated.

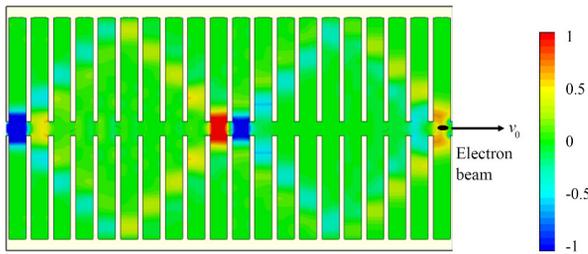


Figure 2: E_z plot. Red: decelerating, blue: accelerating.

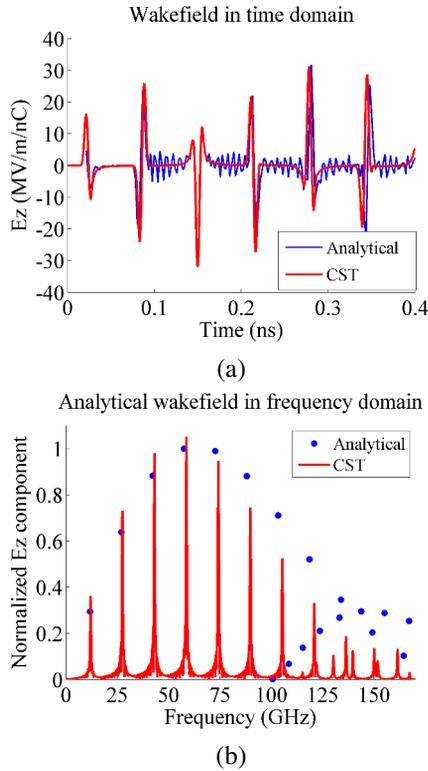


Figure 3: Benchmark the analytical theory with the CST Wakefield Solver in (a) time domain, (b) frequency domain.

Benchmark, Scaling and Nominal Design

A benchmark case is run using the CST solver, with the cavity radius $R = 9.8$ mm, the cavity length $d = 1.5$ mm and the cavity iris thickness 0.5 mm. The drive bunch is a 10 nC Gaussian bunch with $\sigma_z = 0.6$ mm at 70 MeV. The wakefield in the time and the frequency domain is compared in Fig. 3, and the two methods are in good agreement.

The analytical method enables a fast scaling study of the gradient with the structure and beam parameters. It is found that a higher gradient can be achieved with a shorter bunch and a shorter period. The beam hole size is neglected in the analytical model, but the numerical study shows that a smaller beam hole can also increase the gradient.

A nominal design based on the AWA beam parameters is shown in Table 1. The rep rate of the AWA bunch train is 1.3 GHz, so the fundamental frequency of the nominal design is set as its 9th harmonic, 11.7 GHz.

Table 1: A Nominal Design with the AWA Parameters

Charge	σ_z	Energy	R	Hole radius
10 nC	0.6 mm	70 MeV	9.8 mm	0.5 mm
d	Iris thickness	r_s	Gradient	
1.5 mm	0.5 mm	37 M Ω /m	200 MV/m	

ELLIPTICAL STRUCTURE

The bouncing field pattern of the deep corrugation structure in Fig. 2 inspires the idea of the elliptical subwavelength waveguide for TBA. The structure is shown in Fig. 4. The drive and the witness bunch pass through two focal points of the ellipse. The decelerating wake of the drive bunch at one focal point first expands (Fig. 5 (a)), and then it is reflected at the elliptical wall and changed to the accelerating wake. It keeps propagating towards the other focal point where the witness bunch passes through (Fig. 5 (b)).

For a 10 nC, 70 MeV drive bunch, a gradient of 100 MV/m is estimated with both the beam hole radii being 0.5 mm.

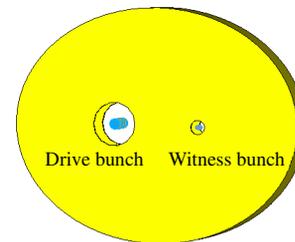


Figure 4: Elliptical corrugated structure illustration.

WAGON WHEEL MTM STRUCTURE

In the above structures for the WFA application, wave propagation in the longitudinal direction and cell-to-cell coupling are not necessary. Next we present a MTM structure with a propagating wave below the TM_{01} cut-off frequency for the application of a power extractor.

Design and Simulation

The wagon wheel structure is a periodic subwavelength structure with the unit cell shown in Fig. 6 (a). The design

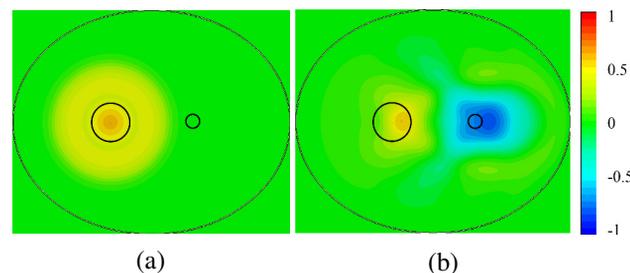


Figure 5: Longitudinal E field. (a) Expanding of decelerating wake (red). (b) Focusing of accelerating wake (blue).

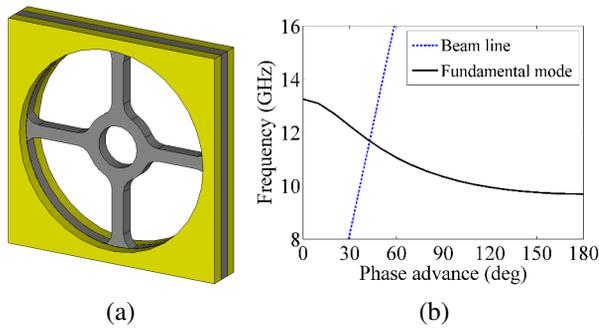


Figure 6: Wagon wheel structure unit cell design. (a) Geometry. The four spokes are 1 mm thick as a scale. The period is 3 mm. Yellow: copper, grey: stainless steel. (b) Dispersion of the fundamental TM-like mode.

has a reasonable microstructure size of 1 mm. The TM-like fundamental mode has a negative group velocity and interacts with the relativistic beam at 11.7 GHz. Fig. 6 (b) shows the dispersion curve of the fundamental mode.

Based on the above unit cell, a power extractor with 12 cells is designed, as shown in Fig. 7. Small slots are cut at the two end cells, and tapers are used to connect the coupling slots to the X-band WR90 waveguides as output ports.

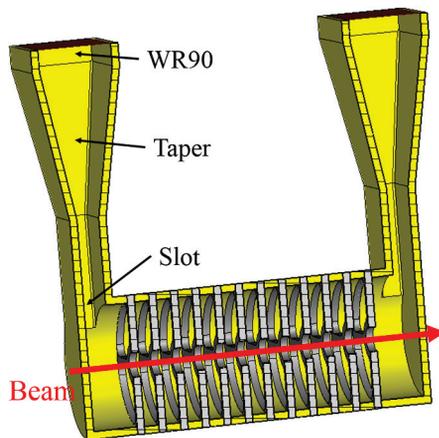


Figure 7: Power extractor design with 12 cells.

CST Microwave Studio is used to simulate the S_{21} parameter, as in Fig. 8 (a). There is a passband around the design frequency 11.7 GHz. The CST Particle Studio PIC solver is used to study the power extracted from a 10 nC Gaussian electron bunch with $\sigma_z = 0.6$ mm. The output peak power is 1.8 MW with a pulse length of about 1 μ s.

Fabrication of Cold Test Structure

A cold test structure with 12 cells is being built. It is designed as a clamped structure of 12 wagon wheel plates in stainless steel and 11 spacer plates in copper, together with additional supporting plates. Two output horns are fabricated separately and brazed to the rest of the structure. The complete drawing and the fabricated plates are shown in Fig. 9.

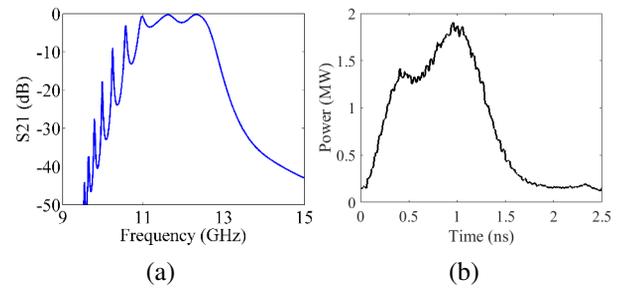


Figure 8: CST simulation results of the 12-cell structure. (a) S_{21} . (b) Output power at 11.7 GHz with a drive bunch of 10 nC charge and 0.6 mm long.

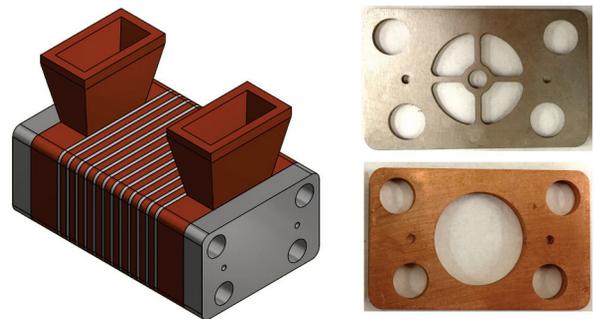


Figure 9: Cold test structure. Left: drawing. Right: Fabricated wagon wheel plate and spacer plate by wire EDM.

CONCLUSIONS

The deep corrugation structure is a promising candidate for the collinear metallic WFA, and a design for the AWA is shown to generate an accelerating gradient of 20 MV/m/nC.

The elliptical structure is a novel idea to do TBA in one structure utilizing the bouncing field pattern.

The wagon wheel MTM structure has a TM-like backward wave as the fundamental mode. A power extractor at 11.7 GHz is designed for the AWA, and 1.8 MW output power is predicted by simulation from a single 10 nC bunch. Fabrication of the cold test structure is in process.

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