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EXPERIMENTS WITH METAMATERIAL-BASED METALLIC ACCELERATING STRUCTURES

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Abstract

We present experimental studies of metamaterial (MTM) structures for wakefield acceleration. The MTM structure is an all-metal periodic structure with its period much smaller than the wavelength at X-band. The fundamental TM mode has a negative group velocity, so an electron beam traveling through the structure radiates by reversed Cherenkov radiation.

Two experiments have been completed at the Argonne Wakefield Accelerator (AWA), namely the Stage-I and Stage-II experiments. Differences between the two experiments include: (1) Structure length (Stage-I 8 cm, Stage-II 20 cm); (2) Bunch number used to excite the structure (Stage-I up to 2 bunches, Stage-II up to 8 bunches). In the Stage-I experiment, two bunches with a total charge of 85 nC generated 80 MW of RF power in a 2 ns long pulse. In the Stage-II experiment, the highest peak power reached 380 MW in a 10 ns long pulse from a train of 8 bunches with a total charge of 224 nC. Acceleration of a witness bunch has not been demonstrated yet, but the extracted power can be transferred to a separate accelerator for two-beam acceleration or directly applied to a trailing witness bunch in the same structure for collinear acceleration.

INTRODUCTION

Metamaterials (MTMs) refer to a category of periodic structures with the period much smaller than the operating wavelength, so they can be treated as artificial media with the effective permittivity ϵ and permeability μ determined by the unit cell design. MTMs are built out of natural materials, while by arranging the subwavelength periodic elements in carefully designed shapes and patterns, novel electromagnetic properties not found in nature can be realized in MTMs, such as a negative refractive index from double negative ϵ and μ. Many interesting applications have been demonstrated on double negative MTMs, including perfect lens, cloaking and advanced antennas [1].

For active MTMs where a relativistic beam is present, the novel physics phenomenon is the reversed Cherenkov radiation [2, 3]. In normal materials with a positive refractive index $n > c/v$, where c is the speed of light and v is the speed of the beam, Cherenkov radiation travels forward with respect to the beam. In this case, the energy flow and the wave vector are parallel. By contrast, in the reversed Cherenkov radiation, energy flow is antiparallel with the wave vector, so the energy flows backward with respect to the beam. This paper investigates the application of the reversed Cherenkov radiation in MTMs to wakefield acceleration excited by short electron bunches.

Structure-based wakefield acceleration (SWFA) [4–7] is an advanced acceleration concept, where a high charge drive beam traverses a wakefield structure in vacuum and transfers its energy by wakefield radiation to a high power radiofrequency (RF) pulse. The RF pulse can then be used to accelerate a witness beam in the same structure behind it (collinear wakefield acceleration) or in a different structure for the witness beam (two-beam acceleration). SWFA is promising to achieve high gradient acceleration, since the RF breakdown rate increases with gradient and decreases with pulse length [8]. As a result, SWFA operating at short RF pulses (a few nanoseconds) has a better chance to eliminate RF breakdowns at high gradient.

To make the structure withstand high power and high gradient wakefield, we designed it as an all-metal MTM structure. The advantages of such a design include resistance to beam damage, possibilities to optimize in the huge parameter space of the MTM unit cell and high shunt impedance and high group velocity at the same time to maximize the extracted RF power.

The following sections will first introduce the experimental facilities at the Argonne Wakefield Accelerator (AWA) [9], and then introduce two experiments carried out there on X-band MTM structures, Stage-I experiment with a 8 cm long MTM structure driven by up to two bunches, and Stage-II experiment with a 20 cm long MTM structure driven by up to eight bunches.

EXPERIMENTAL FACILITIES

The MTM structures built by MIT have been tested at the AWA Facility [9]. Figure 1 shows the drive beam line at AWA. The electron beam with a high charge can be generated by a laser photocathode and then accelerated to 65 MeV in

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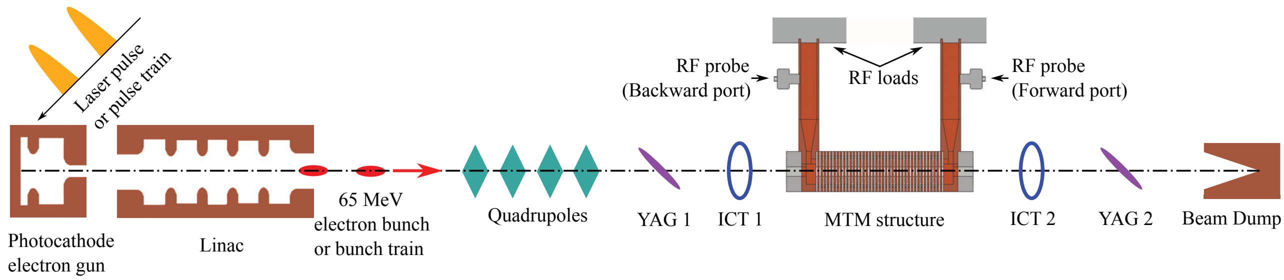
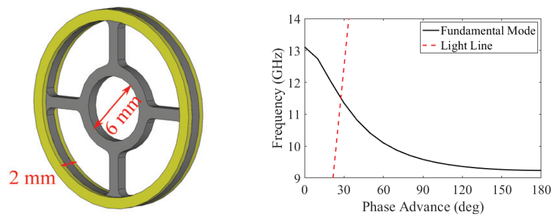


Figure 1: Schematic diagram of the experimental facilities at AWA.



(a) (b)

Figure 2: MTM unit cell design. (a) Unit cell geometry. Beam aperture is 6 mm. The yellow part is in copper and the grey part is in stainless steel. (b) Dispersion curve (frequency vs. phase advance per unit cell) of the fundamental TM mode showing an interaction frequency of 11.42 GHz.

the L-band linacs. Bunch trains are available with 1, 2, 4, 8, ... bunches in a train with a repetition rate of 1.3 GHz. A set of quadrupoles are installed on the beam line to help transport the beam through the structure. The structure is suspended by two X-band waveguides with RF probes mounted. The probe closer to the beam entrance is the backward probe, while the one closer to the beam exit is the forward probe. When the beam travels through, output RF power from the two probes can be measured and compared to verify the reversed Cherenkov radiation. The power measurement was done by a fast oscilloscope. Beam diagnostics available on the beam line include YAG screens to measure the beam transverse profile and integrating current transformers (ICTs) to measure the charge before the structure and the charge transmitted through the structure, respectively.

For the Stage-I experiment [10], the MTM structure is 8 cm long with 40 periods. For the Stage-II experiment, the MTM structure is 20 cm long with 100 periods.

STAGE-I EXPERIMENT

Theory and Simulations

The electromagnetic response of a MTM periodic structure is decided by its unit cell design. The unit cell design we adopted for both the Stage-I and Stage-II experiments is called the 'wagon wheel' design, with a single period shown in Fig. 2 (a). One unit cell with the length $p = 2$ mm is comprised of a 1 mm thick stainless steel 'wagon wheel' plate and a 1 mm thick copper spacer plate. There are 40 periods in the Stage-I structure, so the total structure length is $L = 8$ cm. Figure 2 (b) shows the dispersion curve (frequency vs. phase advance per period $\psi = k_z p$) of the fundamental eigenmode, which is a TM mode with a negative group velocity $v_g = -0.158\ c$. The mode interacts with the 65 MeV beam at 11.42 GHz. The outer waveguide diameter is 16 mm, and an empty waveguide with this diameter would have a cutoff frequency of 14.2 GHz. The below-cutoff design provides a negative permeability μ, and the 'wagon wheel' design provides a negative permittivity ϵ. As a result, a backward MTM mode can propagate in the structure.

The beam aperture is 6 mm, as the optimized design to maintain a high shunt impedance while allowing high charge to be transmitted through. When a single electron bunch traverses the structure with a charge $q = 45$ nC and a longitudinal (z direction) Gaussian distribution of $\sigma_z = 1.2$ mm, the output power P at the backward port is given by

$$P = q^2 k_L |v_g| \left(\frac{1}{1 - v_g/c} \right)^2 \Phi^2 = 25\ \text{MW}, \qquad (1)$$

where $k_L = (\omega/4) \cdot (r/Q)$ is the loss factor, $r/Q = 21$ kΩ/m as the shunt impedance per meter over the quality factor, and $\Phi = \exp[-(k_z \sigma_z)^2/2]$ is the form factor for the Gaussian bunch. The generated RF pulse length t_p is given by

$$t_p = L/|v_g| + L/c = 2\ \text{ns}. \qquad (2)$$

Numerical simulations were performed with the CST Particle Studio Wakefield and Particle-in-cell (PIC) solvers. The complete MTM structure with two output couplers was simulated, and the model is shown in Fig. 3 (a). The extracted microwave power from a single 65 MeV bunch with 45 nC charge is shown in Fig. 3 (b). The backward port receives much higher power compared to the forward port, indicating the reversed Cherenkov radiation. The power level at the backward port agrees with the analytical calculation in Eq. (1). Figure 3 (c) is a longitudinal electric field E_z plot on the middle plane, with red regions being decelerating to electron beams, and blue regions being accelerating. If a witness beam were placed at one of the blue regions, it could get accelerated in the collinear wakefield acceleration regime. Alternatively, the extracted power could be guided into another witness beam line for two-beam acceleration.

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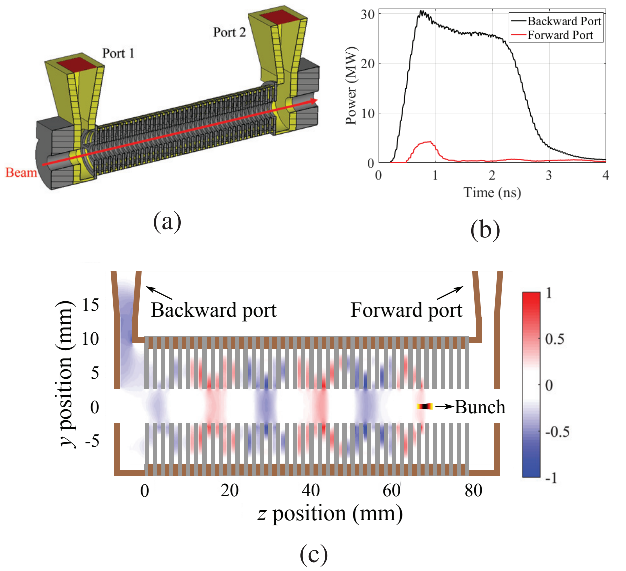

Figure 3: Numerical simulations in the CST Particle Studio. (a) Complete model of the 40-cell Stage-I structure. (b) Extracted microwave power at the two output ports. (c) Plot of longitudinal electric field E_z excited by a bunch traveling to the right on the middle plane.

Experimental Results

In the Stage-I beam best, single bunches up to 45 nC were transmitted through the MTM structure. Figure 4 (a) shows the power traces in the two output ports, and Fig. 4 (b) shows the frequency spectrum, benchmarked with the simulation results. The frequency bandwidth of 0.5 GHz comes from the pulse length t_p = 2 ns. In good agreement with the analytical and simulation results, 25 MW of microwave power was measured in the backward port at 11.4 GHz. This power level corresponds to 28 MV/m of decelerating field on the drive bunch.

The experiment also verified the reversed Cherenkov radiation in the MTM structure by measuring a much higher power in the backward port than in the forward port. Compared to a traveling-wave structure with a positive group velocity in which the drive beam radiates its energy by the normal Cherenkov radiation [11], the reversed Cherenkov radiation leads to a more intense beam-wave interaction and thus a higher extracted RF power.

The peak power can be pushed higher by using a train of two bunches when their generated wakefield adds up coherently. The spacing between the two bunches could be tuned around the nominal bunch repetition rate of 1.3 GHz, so the RF pulses from two bunches with a varied phase difference could be measured, and the results are shown in Fig. 5. Figure 5 (a), (b) and (c) present the voltage signals at the backward port from a single bunch, two bunches in phase with each other, and two bunches out of phase with each other, respectively. Here we define a superposition factor R as $R = (2V_t/q_t)/(V_1/q_1+V_2/q_2)$, where q_1, q_2 and q_t are the charge in Bunch 1, Bunch 2 and the bunch train, respectively,

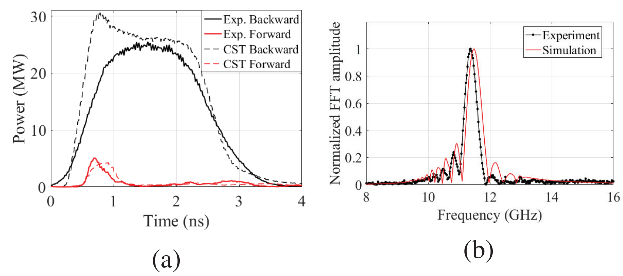

Figure 4: Measured RF pulse from a single 45 nC bunch in the Stage-I experiment benchmarked with the CST PIC simulation. (a) Microwave power in the two ports. (b) Frequency spectrum of the signal at the backward port.

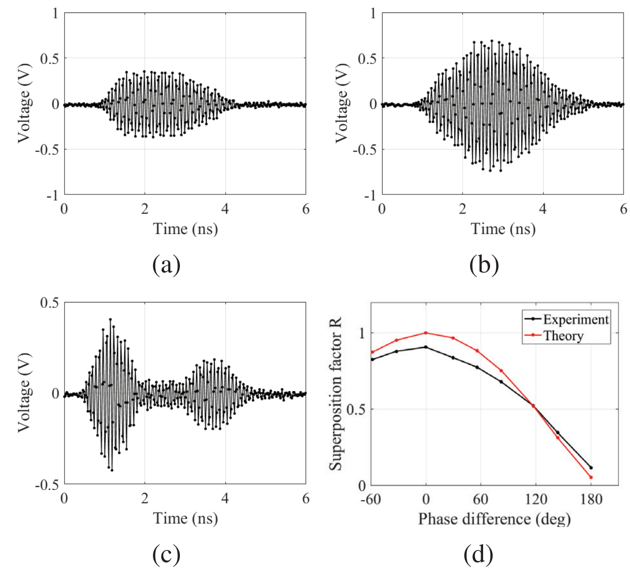

Figure 5: Beam test results from two 4 nC bunches. Voltage signal from (a) a single bunch, (b) two bunches with 0 degree phase difference, (c) two bunches with 180 degrees of phase differenceof X-band. (d) Variation of the superposition factor R with the phase difference in X-band between the two bunches.

and V_1, V_2 and V_t are the voltage amplitude from Bunch 1, Bunch 2 and the bunch train, respectively. R varies from 0 to 1, with $R = 1$ indicating complete adding and $R = 0$ indicating complete canceling of the signals from the two bunches. Figure 5 (d) shows the variation of R with the phase difference (X-band phase) between the two bunches, in good agreement with theory.

The highest power achieved in the Stage-I experiment was generated by two bunches with a total charge of 85 nC in phase with each other. Figure 6 shows the RF power plot at the backward port with a peak power of 80 MW, and the decelerating gradient on the drive beam is 50 MV/m.

A higher power could be achieved if the wakefield from more bunches is added up coherently. However, for the 8 cm long Stage-I structure, the RF pulse from a single bunch with a pulse length of t_p =2 ns can only cover a total of 3 bunches

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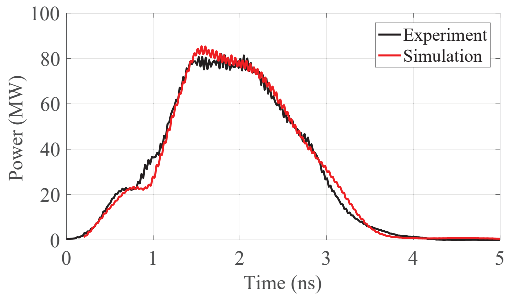

Figure 6: Highest microwave power in the Stage-I experiment from two bunches with a total charge of 85 nC in phase with each other.

with a spacing of $t_b = 1/(1.3\ \text{GHz}) = 0.77$ ns. This means that the extracted power saturates with 3 bunches. To enable coherent wakefield superposition from more bunches in a train, we need a longer structure; this is the motivation for the Stage-II experiment, where a longer 'wagon wheel' structure with 100 cells and 20 cm long was designed to be driven by 8-bunch trains for a higher peak power.

STAGE-II EXPERIMENT

Changes in Structure Design

An illustration of the Stage-II experiment is shown in Fig. 7. The 20 cm long structure is suspended by one straight waveguide connected to the backward port, and one bent waveguide connected to the forward port. The new waveguide system is designed to fit the Stage-II structure in the same vacuum chamber as in the Stage-I experiment.

The Stage-II structure has a similar unit cell design as the Stage-I structure, with the same beam aperture of 6 mm and the same period of 2 mm. The interaction frequency is tuned to 11.68 GHz by changing the waveguide outer radius. In this way, the RF frequency is closer to the 9$^{\text{th}}$ harmonic of the 1.3 GHz nominal beam repetition rate to facilitate the 8-bunch train operation. The group velocity of the fundamental TM mode is -0.154 c at the interaction frequency. The extracted microwave pulse length is 5 ns for a single bunch and 10 ns for a train of 8 bunches by the analytical theory in Eq. (2).

Experimental Results

The drive beam was sent through the Stage-II structure with 1, 2, 4 or 8 bunches in a train. The highest power shot was generated by a train of 8 bunches with a total charge of 224 nC before the structure. The wakefield in the structure built up as the bunches entered the structure one after another. The later bunches in the train experienced a strong wakefield on top of the strong space charge field from itself, so part of the beam was lost in the structure leading to a beam transmission of 86.5% for the 8-bunch train. The total transmitted charge was 194 nC after the structure. The effective charge contributing to the radiated wakefield is between

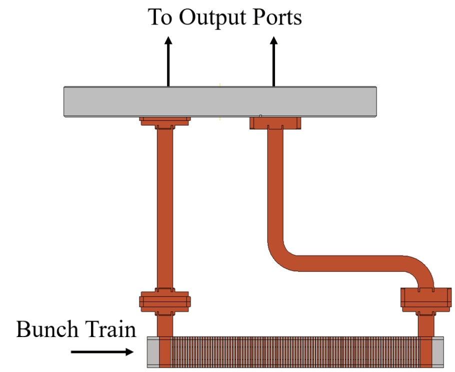

Figure 7: Drawing of the 100-cell Stage-II MTM structure. One straight waveguide and one bent waveguide are brazed onto the top flange of the vacuum chamber, and the longer 20 cm long structure is suspended by the two waveguides.

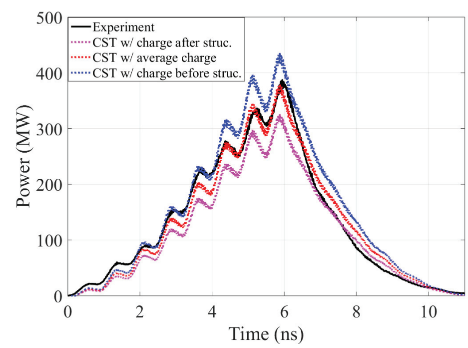

Figure 8: Highest microwave power from 8 bunches with a total charge of 224 nC before the structure and 194 nC after the structure (beam transmission 86.5%). The three simulation curves are plotted assuming that the effective charge contributing to the extracted RF power is the charge before the structure, the charge after the structure and the average of the two.

224 nC and 194 nC, depending on the locations of beam collisions with the structure.

The power trace measured at the backward port is shown in Fig. 8. The peak power reached around 380 MW, corresponding to a decelerating gradient of 110 MV/m on the 8$^{\text{th}}$ bunch in the train. The simulations in Fig. 8 were performed assuming that the effective charge contributing to the extracted RF power is the charge before the structure, the charge after the structure, and the average of the two, respectively. Among the three simulation curves, the experimental result agrees best with the average charge case.

Figure 9 shows the frequency spectra when the drive beam is a single bunch in Fig. 9 (a) and a 8-bunch train in Fig. 9 (b). The measured spectra peak at 11.68 GHz and in both cases agree very well with the CST PIC simulations. In Fig. 9 (b), the two small bumps around 10.3 GHz and 13 GHz are the result of the superposition of the 11.7 GHz signal from the structure interaction frequency and the 1.3 GHz signal from the beam repetition rate.

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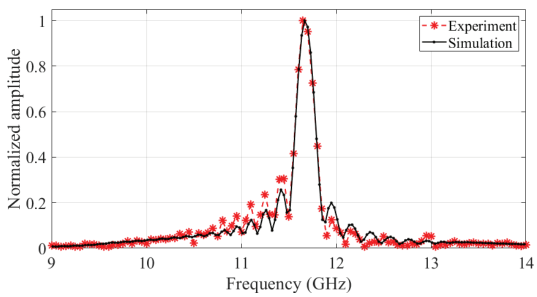
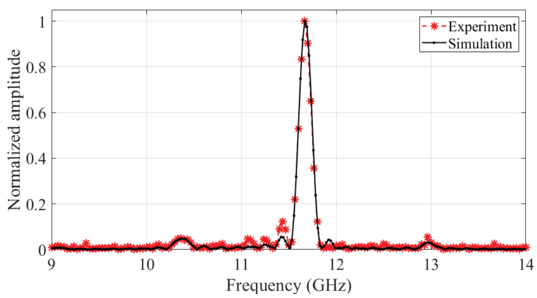


(a)



(b)

Figure 9: Frequency spectra of the Stage-II structure driven by: (a) a single bunch, (b) a train of 8 bunches.

CONCLUSIONS

Two X-band 'wagon wheel' MTM structures have been tested at the 65 MeV AWA drive beam line. In the Stage-I experiment with the 40-cell structure, a single bunch with a charge of 45 nC and an rms length of $\sigma_z = 1.2$ mm generated 25 MW, 2 ns microwave pulses at 11.42 GHz. The reversed Cherenkov radiation was verified in experiment with the backward port receiving much higher power than the forward port. Two bunches with a total charge of 85 nC generated a peak power of 80 MW, and the decelerating gradient was 50 MV/m. In the Stage-II experiment with the 100-cell structure, 8 bunches with a total charge of 224 nC before the structure generated a peak power of 380 MW, and this corresponds to a peak decelerating gradient of 110 MV/m on the 8th bunch in the train. These experiments have revealed the great potential of the 'wagon wheel' structure as a candidate for structure-based wakefield acceleration in either the collinear regime or the two-beam acceleration regime.

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REFERENCES

[1] R. Marqués, F. Martín, and M. Sorolla, *Metamaterials with negative parameters: theory, design, and microwave applications* (John Wiley & Sons, Hoboken, NJ, 2008).

[2] S. Antipov *et al.*, "Observation of wakefield generation in left-handed band of metamaterial-loaded waveguide", *J. Appl. Phys.*, vol. 104, p. 014901, 2008.

[3] X. Lu *et al.*, "Modeling of the interaction of a volumetric metallic metamaterial structure with a relativistic electron beam", *Phys. Rev. ST Accel. Beams*, vol. 18, p. 081303, 2015.

[4] CLIC Conceptual Design Report, Tech. Rep. (CERN).

[5] C. Jing *et al.*, "Electron acceleration through two successive electron beam driven wakefield acceleration stages", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 898, p. 72, 2018.

[6] J. Shao, `arXiv:1907.01069`, 2019.

[7] B. D. O'Shea *et al.*, "Observation of acceleration and deceleration in gigaelectron-volt-per-metre gradient dielectric wakefield accelerators", *Nat. Commun.*, vol. 7, p. 12763, 2016.

[8] A. Grudiev *et al.*, "New local field quantity describing the high gradient limit of accelerating structures", *Phys. Rev. ST Accel. Beams*, vol. 12, p. 102001, 2009.

[9] AWA Facility website, `https://www.anl.gov/awa/awa-facility`.

[10] X. Lu *et al.*, "Generation of High-Power, Reversed-Cherenkov Wakefield Radiation in a Metamaterial Structure", *Phys. Rev. Lett.*, vol. 122, p. 014801, 2019.

[11] J. H. Shao *et al.*, "Recent two-beam acceleration activities at Argonne Wakefield Accelerator Facility", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 3305–3307. `doi:10.18429/JACoW-IPAC2017-WEPVA022`