ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPR26

TEST OF A METAMATERIAL STRUCTURE FOR STRUCTURE-BASED WAKEFIELD ACCELERATION

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Abstract

Metamaterial accelerators driven by nanosecond-long RF pulses show promise as candidates for structure wakefield acceleration. Recent high-power tests at the Argonne Wakefield Accelerator (AWA) with an X-band metamaterial structure have achieved a gradient of 190 MV/m when the structure was excited. A new acceleration regime is also observed, the breakdown-insensitive acceleration regime (BIAR), where the RF breakdown may not interrupt the acceleration of a main beam. Statistical analysis between different breakdown types reveals that the characteristics of the BIAR breakdown are beneficial to high-gradient acceleration at short pulse lengths.

INTRODUCTION

Radiofrequency (RF) breakdown is one phenomenon of great concern in RF accelerators, where a loss in transmitted power is observed accompanied by the emission of surface electrons emitted by high surface fields [1]. Although many studies have been conducted surrounding RF breakdown, the phenomena still have yet to be described by a conclusive theory. Studies on novel structures, operated with nanosecond long drive RF pulses have shown promise at making the effects of RF breakdown less impact. Among these novel accelerator designs is a class of metamaterial (MTM) structures that possess the feature of a negative group velocity [2, 3]. The feature overcomes a trade-off between the accelerator figures of merit, $[\frac{r}{Q}]$, and the group velocity, increasing the beam-wave interaction, and in turn, increasing the achievable accelerating gradient in the short-pulse regime.

This paper discusses the experimental results of the high-power test of an MTM accelerator, operated in the short-pulse regime. A new regime of RF breakdown is observed, the breakdown insensitive accelerating regime (BIAR), where the RF breakdown events may not disrupt the structure operation as a direct result of the short-pulse operation. Preliminary simulations are also presented.

EXPERIMENTAL SETUP

Figure 1(a) shows a full experimental schematic. The geometry of the metamaterial unit cell and the exploded view of the full structure design can be seen in Figs. 1(b) and 1(c), respectively. In the high-power test, the AWA drive-beam line was used to excite a disk-loaded X-band power extraction and transfer structure (PETS). The beamline uses a laser pulse train to generate electron bunch trains that excite the wakefield in the PETS. The generated high-power wakefield was then coupled to the accelerating structure. The total bunch train charge determines the power level of the excitation. The directional couplers couple the forward power into the MTM structure, the transmitted power through, and the reflected power back. The upstream and downstream of the beam pipe have a photodiode and camera, and a Faraday cup, respectively, to collect dark current and light associated with field emission during the high power runs. This is a high-power breakdown test with no witness beam in the MTM structure.

EXPERIMENTAL RESULTS

During the high-power tests, over 3×10^5 pulses were accumulated. Sample RF pulses from the run can be seen in Figure 2(a), including the input RF pulse extracted from the PETS, and the theoretical and experimental transmitted and reflected waves. The theoretical traces are calculated using the time-domain convolution of the input waveform and the S-parameter corresponding to the reflected and transmitted signals. Theoretical pulses show good agreement with the measured pulses and were further verified using time and time domain simulations using CST, as shown in Fig. 2(b). A peak, on-axis gradient of 190 MV/m was achieved when the structure was driven by RF pulses with a 115 MW peak power and a 6 ns FWHM pulse width. Also, the breakdown insensitive acceleration regime [2] was observed during the run. In this regime, the primary RF pulses used for acceleration are not disturbed but there is a disturbance in the secondary pulses, a direct benefit of the short pulse operation. Figure 3 shows sample pulses for the three types of events observed during operation: 3(a) a non-breakdown pulse where the experimental pulses agree with the analytical pulse, 3(b) a BIAR event where the primary accelerating pulse is intact but the secondary pulses are disturbed, and 3(c) a destructive breakdown event where RF transmission is disrupted due to RF breakdown. It was reported in [2] that the BIAR regime exhibits statistically similar RF properties to non-breakdown events.

The dark current in the three event types follows different dynamics. Preliminary results of the dark current data together with the fitting results assuming a Fowler-Nordheim (FN) emission model can be seen in Fig. 4. Figure 4(a) shows the peak current and gradient values from the Fara-

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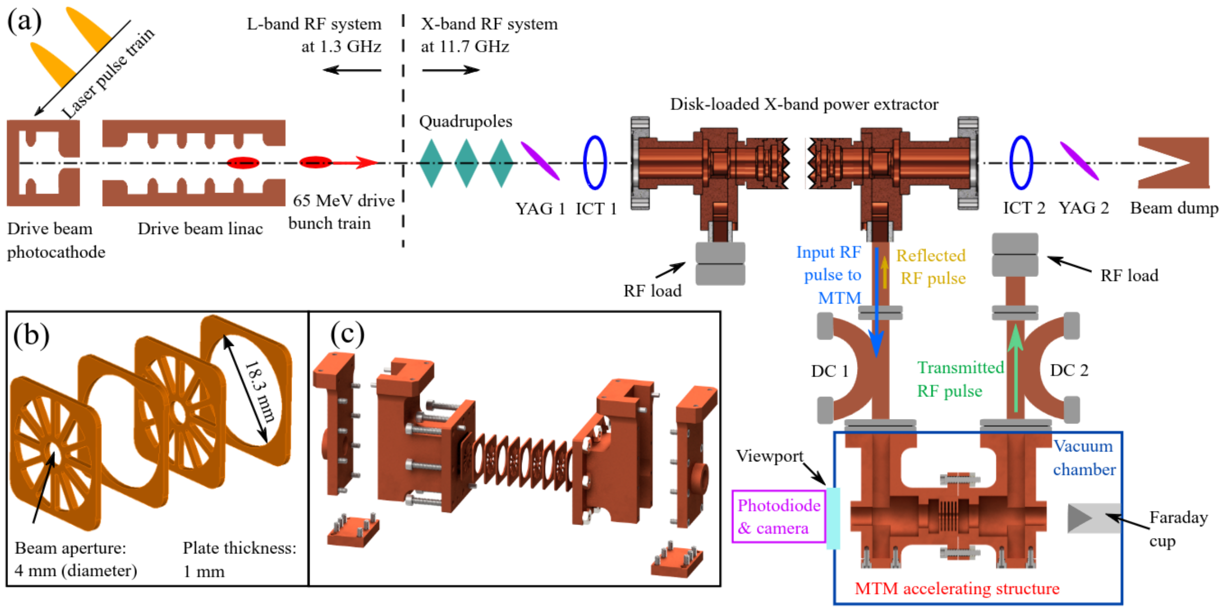

Figure 1: (a) The experimental design, consisting of the AWA drive beamline capable of short-pulse generation via laser excitation at the photocathode. The generated beam is then accelerated toward the PETS, where power is extracted to drive the metamaterial structure. The experiment measures eight total beam line properties: the forward and reflected RF power at each port (six signals total), the voltage converted from the current collision at the Faraday cup, and the photocathode to measure light emitted from dark electrons. The camera allows for observation of light emitted during dark current emission. (b) and (c) show the MTM unit cell and exploded full structure, respectively. [2]

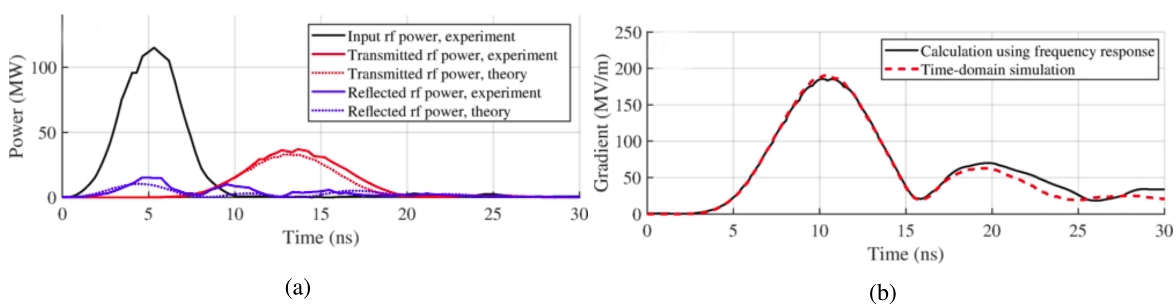

Figure 2: 2(a) Sample waveforms from the experiment, including input RF extracted from the PETS (black curve), the RF transmitted through the MTM structure (red curve), and the reflected signal (blue curve). The theoretical curves are calculated using a convolution of the input RF wave and the respective S-parameter in the time domain. 2(b) Sample gradient calculations using the pulse convolution (black curve) and from time-domain simulations (red curve) in CST using the input pulse from 2(a). [2]

day cup and transmitted RF waveforms, respectively, for non-breakdown events.

Statistical binning using the analytical gradient is needed to accurately group the events, as shown in Fig. 4(a). Figure 4(b) shows the FN log-calculation of the raw data and corresponding fit for 45 data bins and an r^2 of 0.99. Preliminary fitting results with the FN model indicate field enhancement values ranging between 28 and 35; depending on the number of bins used and the strictness of the r^2 value.

DARK CURRENT SIMULATIONS

Preliminary dark current simulations have been conducted using the CST particle-in-cell solver. In the simulations, we assumed a point-like source governed by the FN emission model. The input power and the emitter location are varied while assuming a field enhancement factor (β) of 30. Results thus far indicate that a large portion of the dark current that exits the structure comes from high field areas on the cell faces around the iris downstream of the input RF port. Figure 5 displays the FN log calculation, using the peak current and gradient values from the simulations, at the downstream exit, for an emitter at a radius of 0.085 in along the vertically transverse axis at the downstream-most cell face. The decrease in field enhancement factor from the emitter to the downstream during simulations is observed at all emitters and arises from the transverse field components off-axis.

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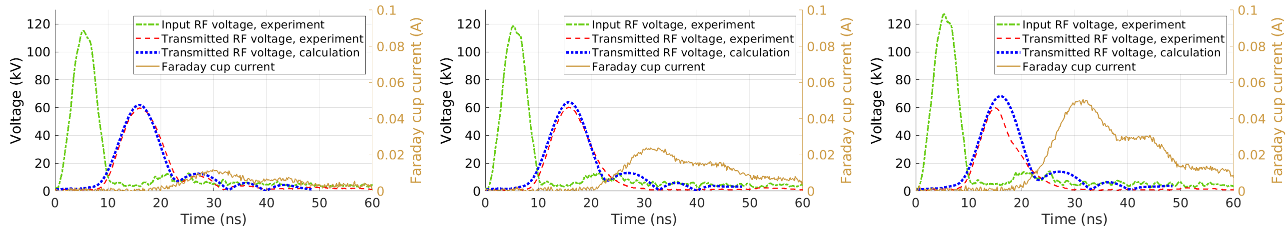
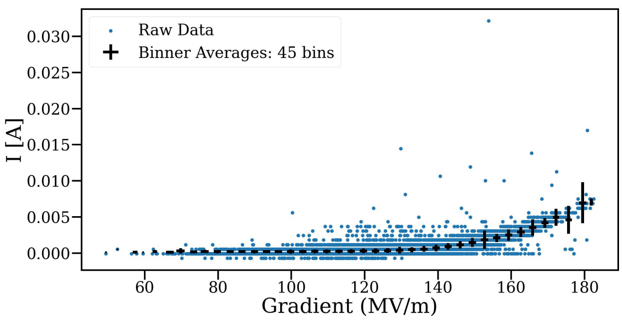
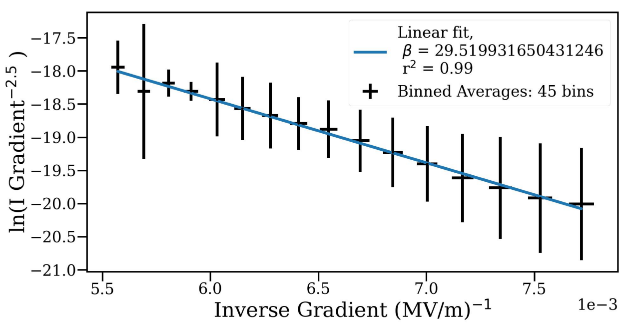


(a) A non-breakdown event (b) A BIAR event (c) A destructive breakdown event

Figure 3: The three types of breakdown events. RF voltages are displayed. The green line indicates the envelope of the signal extracted from the PETS that drives the MTM structure. The blue pulse is the theoretical transmitted pulse calculated. The red pulse is the measured transmitted RF pulse. The yellow curve on the opposite y-axis is the observed voltage reading from the Faraday cup, converted to amps. [2]



(a)



(b)

Figure 4: (a) Experimental peak Faraday cup signal in amps plotted against the peak gradient. The black points represent the binned quantities. (b) Fowler-Nordheim fitting result for the binned data corresponding to the data in Fig. 4(a).

More simulation work is expected to further understand the dynamics of dark electrons in different breakdown types.

CONCLUSION AND FUTURE PLANS

The metamaterial structure designed as an accelerating structure for two-beam acceleration reached 190 MV/m gradients when driven with a 115 MW peak power level with short nanosecond long pulses during the high-power breakdown test. The BIAR regime, a result of the short-pulse operation, is a phenomenon observed and suggests the potential advantages of short-pulse acceleration. Future work

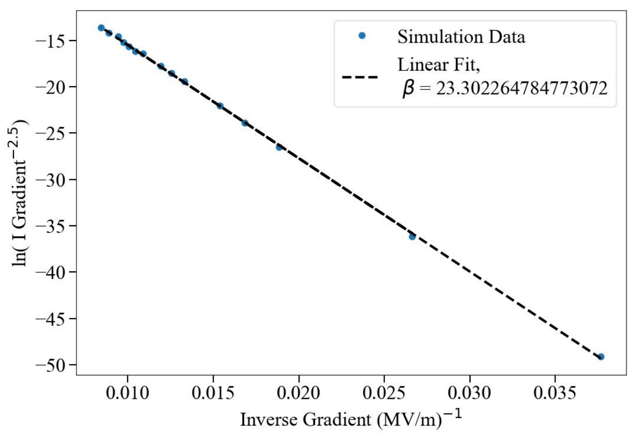


Figure 5: A sample Fowler-Nordheim fitting for the downstream dark current simulations. The emitter location is on the vertically transverse axis, at a radius of 0.085 in, on the cell face furthest downstream in the structure. The current values used for the FN log calculation are taken as the peak values measured, in amperes, at a downstream detector in the simulations. The gradient is taken as the peak-on-axis electric field probe value measured in MV/m.

to better understand dark current emission in different breakdown types in the accelerating structure is in progress.

ACKNOWLEDGEMENTS

This research was supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics under Award DE-SC0021928, and the Chicagoland Accelerator Science Traineeship (CAST) program sponsored by the U.S. DOE award DE-SC0020379. The work at the AWA was funded through the U.S. Department of Energy, Office of Science under Contract No. DE-AC02-06CH11357.

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