High Gradient Wakefields in Dielectric Loaded Structures

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Abstract. Dielectric loaded wakefield structures have potential to be used as high gradient accelerator components. Using the high current drive beam at the Argonne Wakefield Accelerator Facility, we employed cylindrical dielectric loaded wakefield structures to generate accelerating fields of up to 86 MV/m, at 10 GHz. Short electron bunches of up to 86 nC are used to drive these fields, either as single bunches or as bunch trains. The structures consist of cylindrical ceramic tubes (cordierite) with a dielectric constant of 4.76, inserted into cylindrical copper waveguides. These standing-wave structures have a field probe near the outer diameter of the dielectric, in order to sample the RF fields generated by the electron bunches. Monitoring the field probe signal serves to verify the absence of electric breakdown in the structures. MAFIA simulations are used to calculate the amplitude of the fields generated by the traversing electrons bunches.

Keywords: wakefield acceleration, high gradient, dielectric structure
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INTRODUCTION

The Argonne Wakefield Accelerator Facility (AWA) is dedicated to the study of electron beam physics and the development of accelerating structures based on electron beam driven wakefields [1]. In order to carry out these studies, the facility employs a photocathode RF gun capable of generating electron beams with high bunch charges and short bunch lengths (up to 100 nC with a bunch length of 13 ps FWHM). This high intensity beam is used to excite wakefields in the structures under investigation. The wakefield structures presently under development are dielectric loaded cylindrical waveguides with operating frequencies of 10 or 14 GHz.

The facility is also used to investigate the generation and propagation of high brightness electron beams. Presently under investigation, is the use of photons with energies lower than the work function of the cathode surface (Schottky-enabled photoemission [2]), aimed at generating electron beams with low thermal emittance. Novel electron beam diagnostics are also developed and tested at the facility.

The AWA electron beam is also used in laboratory-based astrophysics experiments; namely, measurements of microwave Cherenkov radiation and beam induced fluorescence of air [3].

AWA FACILITY

The AWA high intensity electron beam is generated by a photocathode RF gun, operating at 1.3 GHz. This one-and-a-half cell gun typically runs with 12 MW of input power, which generates an 80 MV/m electric field on its Magnesium cathode surface. A 1.3 GHz linac structure increases the electron beam energy, from the 8 MeV produced by the RF gun, to 14 MeV. The charge of the electron bunches can be easily varied from 1 to 100 nC, with bunch lengths of 2 to 5 ps rms, and normalized emittances of 30 to 200 π mm mrad.

The AWA laser system consists of a Spectra Physics Tsunami oscillator followed by a Spitfire regenerative amplifier and two Ti:Sapphire amplifiers (TSA 50). It produces 1.5 mJ pulses at 248 nm, with a pulse length of 6 to 8 ps FWHM and a repetition rate of up to 10 pps. A final KrF Excimer amplifier is optionally used to increase the energy per pulse to 15 mJ. The generation of electron bunch trains (up to 64 bunches) requires each laser pulse to be divided by means of beam splitters into a laser pulse train. The laser pulses in the train arrive at the photocathode surface separated by an integer number of RF periods, thus ensuring that the electron bunches have the same launch phase.

WAKEFIELD EXPERIMENTS

We have recently built and tested three dielectric loaded wakefield structures. Each one consists of cylindrical ceramic tubes inserted into a cylindrical copper waveguide, as shown in Fig. 1. The ceramic material is known as cordierite, witch has a dielectric constant of 4.76. The insertion of metallic end-pieces with a cut-off frequency above the operating frequency, makes these devices operate as standing-wave structures. A weakly coupled field probe (-60 dB) near the outer diameter of the dielectric cylinders serves to monitor the wakefields generated by the driving electron bunches, and to verify the absence of electric breakdown. Table 1 shows some parameters of the three wakefield structures.

The field probe signal can be sent to an RF mixer circuit used to convert the signal down to 5 GHz, which is then displayed on a high bandwidth oscilloscope (LeCroy

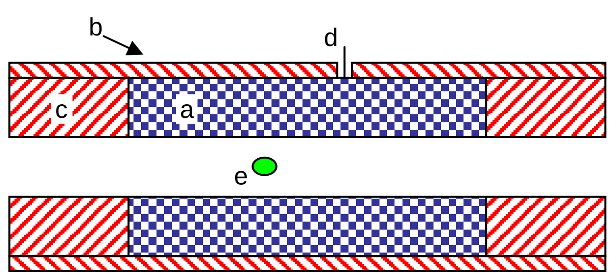

FIGURE 1. Longitudinal cross section of a typical dielectric loaded wakefield structure: (a) hollow dielectric cylinder; (b) copper waveguide; (c) copper end-piece; (d) coaxial antenna used as field probe; (e) electron bunch propagating along the axis of the structure.

TABLE 1. Parameters of Dielectric Structures

Parameter	Structure 1	Structure 2	Structure 3
Inner Diameter	10 mm	10 mm	5 mm
Outer Diameter	15 mm	15 mm	15 mm
Length	102 mm	23 mm	28 mm
Frequency of monopole mode	14 GHz	14 GHz	10 GHz
Gradient (per nC)	0.5 MV/m	0.5 MV/m	1.0 MV/m

Wavemaster 8600A; 6 GHz bandwidth). Alternatively, the probe signal can be sent directly to a higher bandwidth oscilloscope (Tektronix TDS-6154C; 15 GHz bandwidth). Initially, at the time the first structure was tested, the RF mixer circuit was the only option for data acquisition, since the 15GHz bandwidth oscilloscope was not available. Later, the comparison of the two methods verified that they were equally valid. Figure 2 shows the output of the mixer circuit for various bunch charges that propagated through Structure 1. The phase of these signals is arbitrary, since the 9 GHz local oscillator is not phase locked to the klystron that powers the RF gun and linac. Figure 3 shows the peak values (positive and negative) of the wakefields measured for different bunch charges. As expected, the amplitude of the wakefields rises linearly with bunch charge.

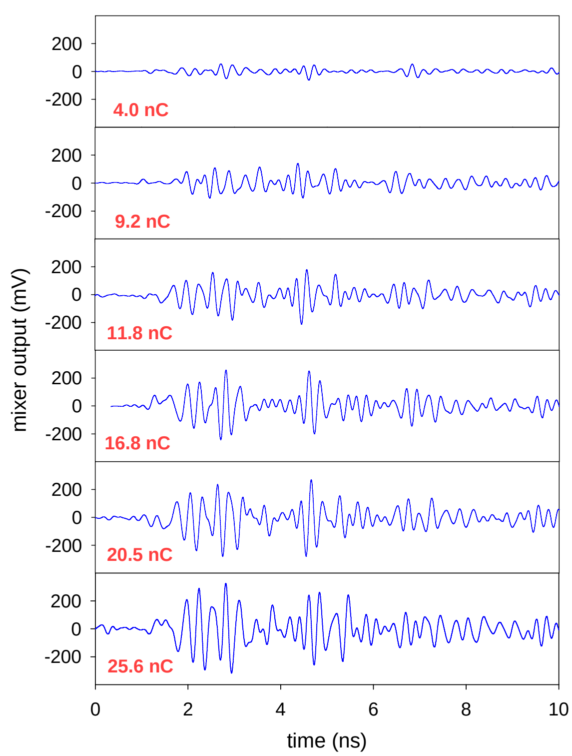

FIGURE 2. Output of RF mixer for various bunch charges that propagated through Structure 1.

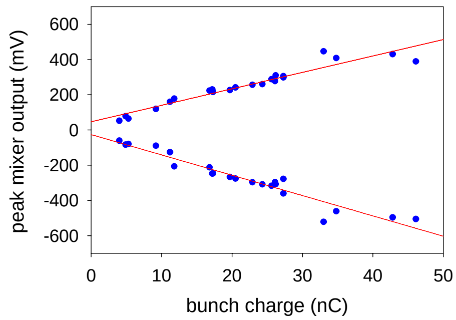

FIGURE 3. Peak values of the RF mixer output plotted as a function of the charge in the drive bunch.

MAFIA simulations show that a 43 nC electron bunch traversing this structure generates a peak axial electric field of 23 MV/m on axis. In this relatively short structure, several longitudinal modes are excited, but the generated RF power is distributed mainly among four modes: $TM_{0,1,9}$, $TM_{0,1,10}$, $TM_{0,1,11}$, and $TM_{0,1,12}$.

Wakefield measurements were also made using two electron bunches separated by 1.5 ns (two RF periods of the klystron frequency). Figure 4 shows the RF mixer output for each bunch alone and also for the two bunches together.

The wakefields in Structure 2 were driven by electron bunches with charges up to 86 nC. MAFIA simulations show that these high bunch charges excite accelerating gradients of 43 MV/m. This structure was identical to Structure 1, except for being shorter. Consequently, different longitudinal modes were excited. The RF power was distributed mostly among the monopole modes TM012, TM013, TM014, and the

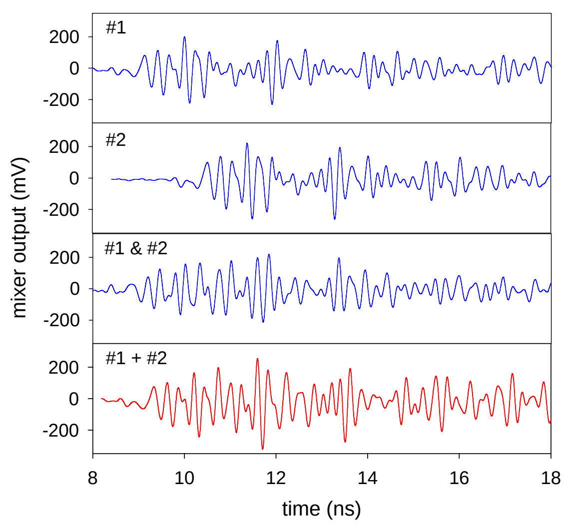

FIGURE 4. RF mixer output showing the signal from: (a) bunch #1 alone; (b) bunch #2 alone; (c) bunches #1 and #2 separated by 1.5 ns (two RF periods of the klystron frequency); (d) numerical addition of the signals from (a) and (b), which is not strictly the correct approach, since the relative phases of these two signals are arbitrary due to the free running local oscillator in the RF mixer circuit. Another caveat is the fact that the laser intensity of the pulse that generates bunch #2 decreases when pulse #1 is present, due to depletion in the excimer laser amplifier; thus, the charge of bunch #2 is lower when bunch #1 is present.

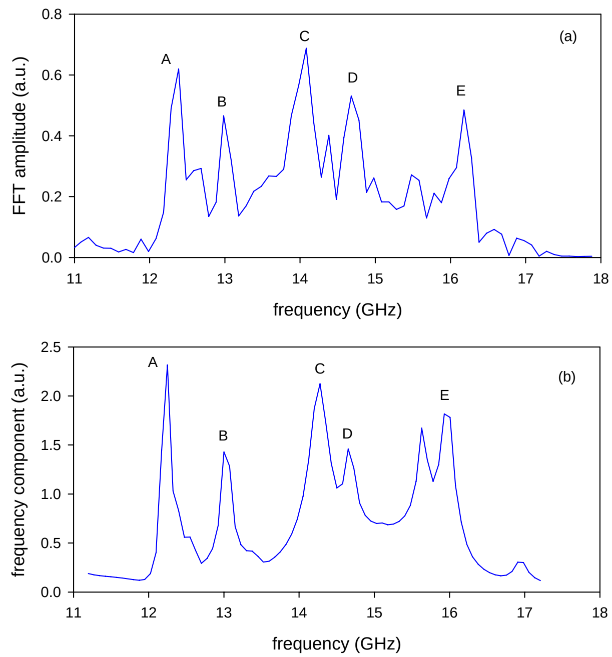

FIGURE 5. FFT of the radial component of the electric field (in arbitrary units), identifying the peaks A, B, C, D, E, respectively, as the modes HEM_{111}, TM_{012}, TM_{013}, HEM_{112}, TM_{014}: (a) measurement; (b) MAFIA simulation, taking into account the measured Q factor of each mode.

dipole modes HEM_{111} and HEM_{112}. The predominance of the monopole modes over the dipole modes depended on the alignment of the electron bunch propagation with the geometric axis of the structure. Figure 5 compares the FFT of the measured radial electric field with the results from MAFIA simulations, identifying the main modes.

Electron bunches of equally high charge (up to 86 nC) were used to drive wakefields in Structure 3. MAFIA simulations show that accelerating gradients of 86 MV/m were reached. The temporal profile of the radial electric field (E_r), as measured by the field probe, is shown in Fig. 6; also shown is its FFT.

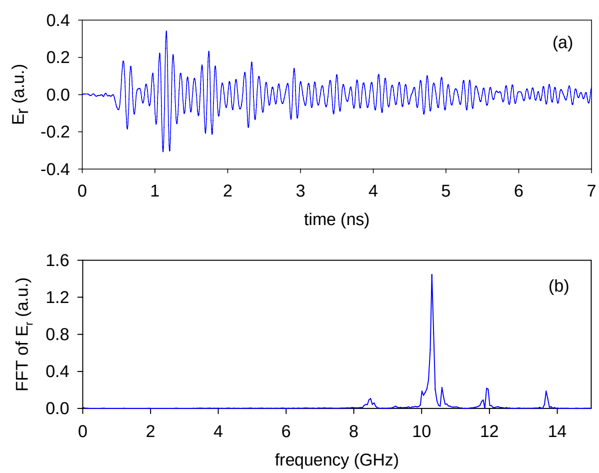

FIGURE 6. Measurement of the radial electric field driven by an 86 nC electron bunch, using the field probe on Structure 3: (a) temporal profile of the radial electric field; (b) the FFT of the signal.

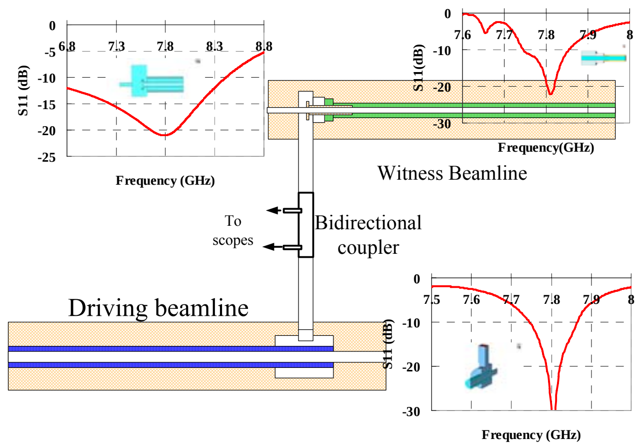

FIGURE 7. Schematic showing the two dielectric loaded structures that comprise the two-beam-accelerator system. The plots show the power transmission parameters predicted by the design of the various components at the operating frequency of 7.8 GHz.

CONCLUSION

Throughout the experiments carried out with these dielectric loaded wakefield structures, there was never any sign of electric breakdown in the structures, even near the highest achieved gradients of 86 MV/m. We are currently designing a new structure to reach accelerating gradients in excess of 100 MV/m.

Presently, the AWA Facility is capable of generating bunch trains of up to four bunches. A new Cesium Telluride photocathode is under development and will allow the generation of much longer high charge bunch trains, and, consequently, longer RF pulses. A new photocathode RF gun, presently under construction, will generate a witness beam (probe) to be accelerated in these dielectric loaded wakefield structures. Thus, once the long drive bunch trains and the witness beam are available, the AWA facility will be fully capable of exploring high gradient acceleration over meter scale distances. Designing of suitable dielectric loaded structures to carry out these two-beam-acceleration experiments is under way (Fig.7), and the first prototype of the power extractor section is presently under construction.

ACKNOWLEDGMENTS

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REFERENCES

1. M.E. Conde et al., “The Argonne Wakefield Accelerator Facility: Capabilities and Experiments,” Proc. of the 2004 Advanced Accelerator Concepts Workshop, AIP Conf. Proc. **737**, p. 657 (2004).
2. Z. M. Yusof et al., *Phys. Rev. Lett.* **93**, 114801 (2004).
3. P. Privitera, private communication.