HIGH GRADIENT EXCITATION AND RF POWER GENERATION USING DIELECTRIC LOADED WAKEFIELD STRUCTURES*

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Abstract

Dielectric loaded wakefield structures are being developed to be used as high gradient accelerator components. The high current electron beam at the Argonne Wakefield Accelerator Facility (AWA) was used to excite wakefields in cylindrical dielectric loaded wakefield structures in the frequency range of 8 to 14 GHz, with pulse duration of a few nanoseconds. Short electron bunches (13 ps FWHM) of up to 86 nC drove these wakefields, and accelerating fields as high as 100 MV/m were reached. Similar structures were used to extract RF power from the electron beam; however, in this case they were traveling-wave structures, driven by electron bunch trains of up to 16 bunches. RF pulses of up to 40 MW were measured at the output coupler of these structures. The AWA electron beam was also used to drive the cavity modes in a metallic standing-wave structure designed and built by SLAC / KEK (originally meant to be powered by a klystron).

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 between 8 and 14 GHz.

The facility is also used to investigate the generation and propagation of high brightness electron beams, and to develop novel electron beam diagnostics.

The AWA electron beam is also used in laboratory-based astrophysics experiments; namely, measurements of microwave Cherenkov radiation and beam induced fluorescence of air [2].

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 15 MeV. The charge of the electron bunches can be easily varied from 1 to 100 nC, with bunch lengths of 2 mm 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 2 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 (presently up to 16 bunches) requires each laser pulse to be divided by means of beam splitters into a laser pulse train.

HIGH GRADIENT WAKEFIELD GENERATION

We have recently built and tested four dielectric loaded wakefield structures. Each one consists of a cylindrical dielectric tube inserted into a cylindrical copper waveguide. The dielectric material is either a ceramic known as cordierite, or quartz. 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 four wakefield structures tested.

Table 1: Parameters of Standing-Wave Structures

SW Structure	# 1	# 2	# 3	# 4
Material	Cordierite	Cordierite	Cordierite	Quartz
Dielectric constant	4.76	4.76	4.76	3.75
Freq. of TM01n	14.1 GHz	14.1 GHz	9.4 GHz	8.6 GHz
Inner radius	5 mm	5 mm	2.75 mm	1.9 mm
Outer radius	7.49 mm	7.49 mm	7.49 mm	7.49 mm
Length	102 mm	23 mm	28 mm	25.4 mm
Maximum charge	46 nC	86 nC	86 nC	75 nC
Maximum gradient	21 MV/m	43 MV/m	78 MV/m	100 MV/m

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Table 1 also lists the maximum bunch charge that traversed each structure, and the accelerating gradient generated in the structure by its passage. These values of gradient result from numerical calculations with the software MAFIA, using the known parameters of the structures and of the electron bunches. The amplitude of the field probe signals are not a reliable way to measure the field gradients, because the calibration of the probe cannot be made accurately enough for the different modes supported by the structures. Thus, the field probe signals are used solely to monitor possible electric breakdown events in the structures.

The field probe signal can be sent directly to a high bandwidth oscilloscope (Tektronix TDS-6154C; 15 GHz bandwidth). Figure 1 shows this signal and its FFT, as seen when electron bunches propagate through structure #4. Due to the field probe geometry, its signal is basically proportional to the radial electric field present at the tip of the probe. A comparison of the FFT of the signal with numerical simulations allows the different peaks to be identified with the various modes supported by the structure.

POWER EXTRACTOR FOR TWO-BEAM-ACCELERATION

The development of the necessary components for two-beam-acceleration experiments is being pursued. Thus, we recently tested a decelerating structure, which has an RF power output coupler as an integral part of the structure. The drive beam of a two-beam-accelerator (TBA) would traverse this so-called power extractor, and the generated RF power would then be coupled out of the decelerator and into the accelerating structure.

This power extractor was installed on the AWA drive beamline, and a calibrated bi-directional RF coupler was connected to its output coupler, to enable the measurement of the RF power generated by the beam.

Single electron bunches were initially put through this structure, generating short RF pulses (about 2 ns FWHM) with a frequency spectrum centered at 7.8 GHz. A maximum peak power of 30 MW was generated by electron bunches of 66 nC. Subsequently, bunch trains consisting of 16 electron bunches were used to generate longer RF pulses; these electron bunches were either spaced by six RF periods of the 7.8 GHz wakefield (one RF period of the 1.3 GHz RF gun), or by twelve periods of the 7.8 GHz wakefield (two RF periods of the 1.3 GHz RF gun). Due to the finite group velocity of the RF packets in the structure, the superposition of the RF fields of the individual bunches involves fewer bunches when they are spaced further part. Figure 2 shows a series of oscilloscope traces from the bi-directional coupler signal, for an increasing number of electron bunches, each separated by six RF periods. Obviously, the larger number of bunches generate longer RF pulses, with narrower frequency spectra. Figure 3 shows the bi-directional coupler signal generated by bunch trains in which the bunches are separated by twelve RF periods. In this case, longer RF pulses are generated, but due to the effective superposition of fewer pulses, the amplitude of the RF pulse is smaller, for a given bunch charge.

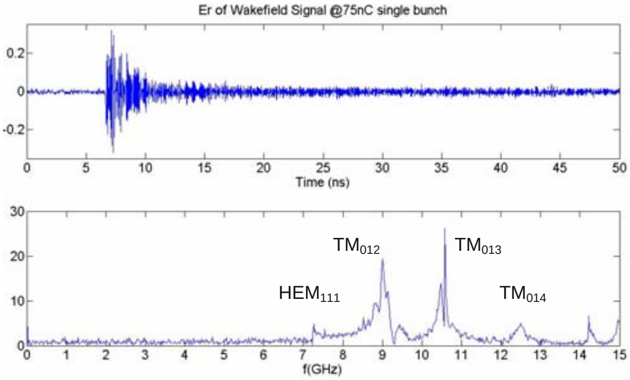

Figure 1: Measurement of the radial electric field driven by a 75 nC electron bunch, using the field probe on Structure 4: (a) temporal profile of the radial electric field; (b) the FFT of the signal.

The highest power generated by this structure was 44 MW, of which 40 MW were actually coupled out, the difference being accounted for by losses in the output coupler. This was achieved with four electron bunches spaced by six RF periods, with a total charge of 107 nC; in this case the pulse length was approximately 4 ns FWHM.

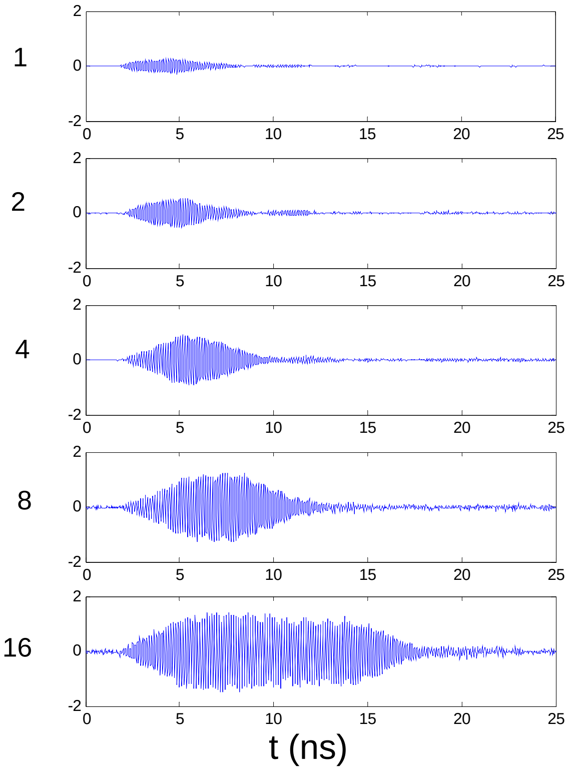

Figure 2: Oscilloscope traces showing the RF pulses sampled by the bi-directional coupler. The number on the left side of the plots indicates the number of electron bunches that propagated through the power extractor.

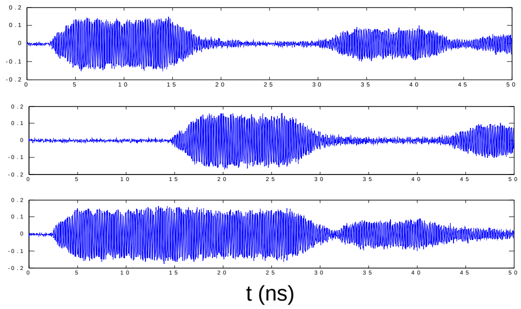

Figure 3: Oscilloscope traces showing the RF pulses sampled by the bi-directional coupler: (a) eight bunches spaced by twelve RF periods; (b) later set of eight bunches spaced by twelve RF periods; (c) sixteen bunches spaced by twelve RF periods.

SLAC / KEK STRUCTURE

Recently, we have performed an experiment at AWA using a metallic iris loaded standing wave X-band structure developed by SLAC and KEK, which was originally meant to be powered by a klystron. The structure, installed in the AWA drive beamline, is shown in Fig. 4. A bidirectional coupler at the coupling port allows the measurement of the wakefields excited by the passage of the drive electron bunch (Fig. 5). The estimated peak wakefield generated is about 50 MV/m for a bunch charge of 80 nC. Also from the figure, a loaded quality factor Q of about 5500 can be estimated. Figure 6 shows the peak electric field measured at the bidirectional coupler as a function of the drive bunch charge; the deviation from the initial linear dependence is due to the slight bunch lengthening that occurs as the bunch charge is increased. One could increase the gradient to much higher levels by using a multiple bunch drive beam. We believe this is an effective way to test properties of high gradient structures, including the excitation of higher order modes.

NEXT STEPS

In the immediate future, the development of dielectric loaded structures will proceed, as well as the testing of more X-band metallic structures driven as wakefield devices: a photonic band-gap structure and more iris loaded standing wave structure (built by SLAC / KEK). A new RF power station, now under fabrication, with an additional 30 MW L-band klystron (on loan from LANL – many thanks!) will greatly increase the capabilities of the AWA facility, by increasing the drive beam energy and enabling experiments with smaller diameter structures. This additional RF power will also allow the operation of a second RF gun, now under fabrication, which will provide the witness beam to directly probe the generated wakefields. The development of a Cesium Telluride photocathode fabrication chamber, now in its final stages, will enable the generation of longer electron bunch trains, with high charge per bunch, which will produce longer wakefield RF pulses with even higher amplitude. The goal is to reach gradients on the order of 0.5 GV/m, and to be able to generate RF pulses with GW power level.

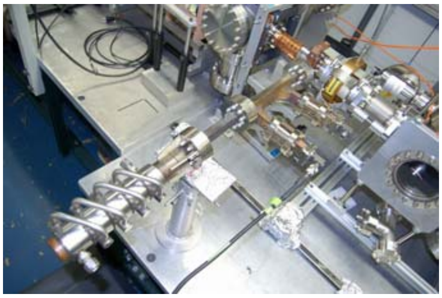

Figure 4: SLAC / KEK X-band structure installed at the AWA beamline.

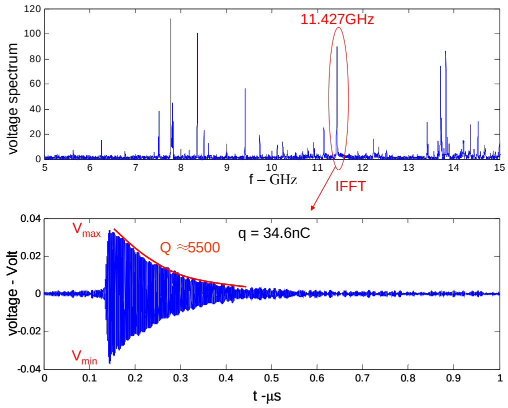

Figure 5: Wakefields observed at bidirectional coupler: (a) FFT of voltage signal; (b) IFFT of 11.4 GHz component only.

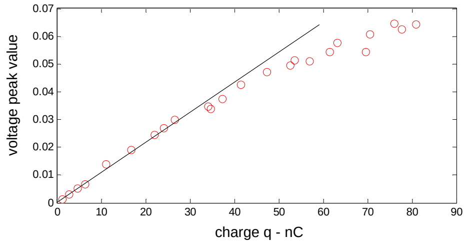

Figure 6: Peak electric field measured at the bidirectional coupler as a function of the drive bunch charge.

REFERENCES

[1] M.E. Conde et al., "The Argonne Wakefield Accelerator Facility: Capabilities and Experiments," Proceedings of the 2004 Advanced Accelerator Concepts Workshop, June 2004.

[2] M. Ave et al., "Measurement of the pressure dependence of air fluorescence emission induced by electrons," Astropart. Phys. 28 (2007) 41.