

SURVEY OF ADVANCED DIELECTRIC WAKEFIELD ACCELERATORS*

M. E. Conde[#], ANL, Argonne, IL 60439, U.S.A.

Abstract

This survey highlights some of the most significant experimental work carried out in the development of dielectric wakefield accelerating structures. Both the collinear and the two-beam-accelerator configurations are presented, and the operating frequencies are in the few GHz range or in the THz regime. Planned future experiments are also briefly discussed.

INTRODUCTION

There has been continued interest in the development of dielectric-loaded wakefield structures that can be used to accelerate particle beams. The present search for materials able to withstand very intense RF fields has renewed this interest.

This paper will focus on discussing experimental work on the subject of dielectric wakefield accelerators. There have been important topics presented in theoretical papers, and also interesting experiments that have been proposed but never carried out; mostly for lack of space, these will not be included in this report.

The early proof-of-principle experiments demonstrated accelerating gradients of less than 1 MV/m, in the late 1980s. In the following decade gradients reached slightly above 10 MV/m. Progress has been steadily made, and, presently, accelerating fields of 100 MV/m at frequencies around 10 GHz, and of multi GV/m at THz frequencies have been observed.

EXPERIMENTS AT ARGONNE

The Advanced Accelerator Research Group at Argonne National Laboratory, initiated by J. Simpson, has been a pioneer in experiments demonstrating dielectric wakefield acceleration. It has had a long history of proof-of-principle experiments and significant advances in the design and testing of dielectric based wakefield structures. The initial wakefield acceleration experiments, conducted at the Argonne Accelerator Test Facility (AATF) in the late 1980s, were followed by many important experiments at the Argonne Wakefield Accelerator Facility (AWA), which was built with the main goal of carrying out wakefield accelerator research.

Wakefield Acceleration at AATF

The AATF had an electron beam produced by an L-band thermionic RF gun followed by two traveling-wave linac structures that brought the beam energy up to 20 MeV. This accelerator complex was built by the Argonne Chemistry Division to carry out experiments in radiolysis, and later provided a beamline for these pioneer wakefield acceleration experiments. The charge per bunch could be

varied between 1 and 5 nC, and there was no provision for the generation of witness bunches to probe the wakefields excited by the drive bunches. A clever scheme was devised to generate the witness bunches: part of the electron beam passed through a carbon target losing some of its kinetic energy; this lower energy fraction of the beam was subsequently separated from the main beam in a dipole magnet and went through an adjustable delay line that allowed the timing between the two bunches to be adjusted; finally, a second dipole magnet brought the two bunches to the beamline where the wakefield structure was installed. Figure 1 shows a plot of the wake potential measured in a cylindrical dielectric loaded wakefield structure [1].

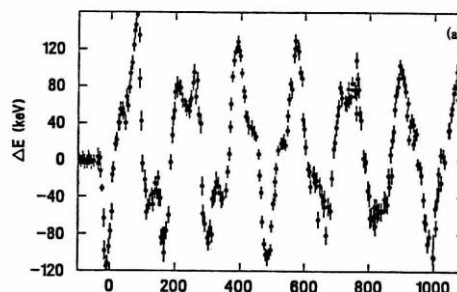


Figure 1: Wakefield potential measured at AATF (the horizontal axis is the delay between the two bunches, in ps).

Wakefield Acceleration at AWA

The AWA facility was built in the early 1990s, having as its main objective the generation of high charge electron beams for wakefield acceleration and RF power generation [2]. A single cell photocathode RF gun was used to produce high charge drive electron bunches of charge up to 100 nC. This 2 MeV drive beam was subsequently accelerated by two linac tanks to an energy of 14 MeV; these standing-wave linac structures were designed with large diameter irises in order to minimize the excitation of deleterious wakefields by the high charge drive bunches. A multi-cell photocathode RF gun [3], fed from the same L-band klystron, was used to generate the 4 MeV witness bunches. An adjustable delay line in the laser beam transport and an RF phase shifter allowed the timing between the drive beam and the witness beam to be adjusted over a wide range, thus allowing the mapping of the wakefields trailing the drive bunches.

The two beamlines – drive beam and witness beam – were connected by a combining section, as shown in Fig. 2. This allowed the two beams to travel through a single wakefield acceleration structure, in the scheme known as collinear wakefield acceleration. Alternatively, the two beams could travel along parallel beamlines, and the wakefield radiation generated by the drive beam in a dielectric loaded structure could be coupled by means of a

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[#]conde@anl.gov

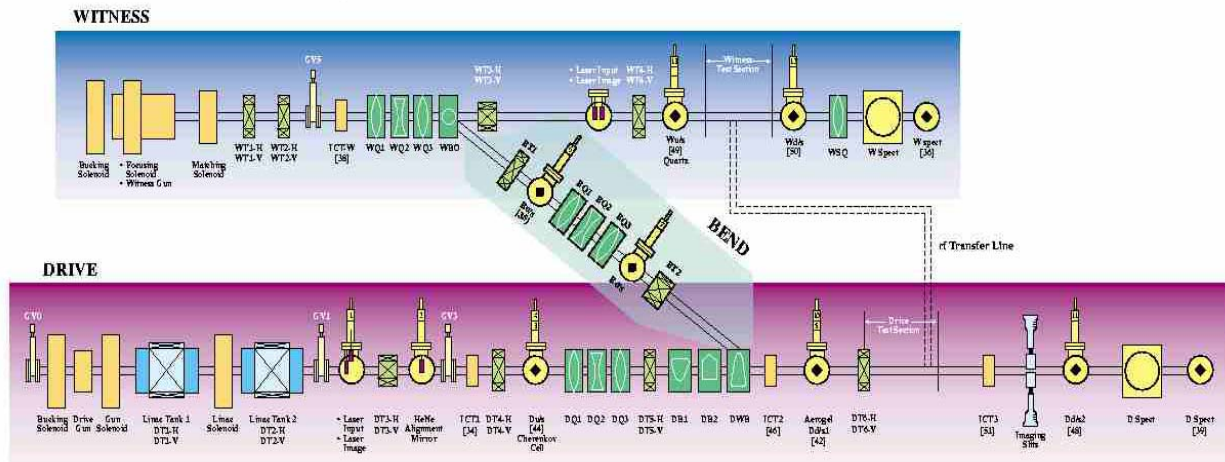


Figure 2: Schematic of AWA beamlines.

waveguide into a second dielectric loaded structure, where the witness beam could be accelerated, in the so-called two beam accelerator (TBA) configuration.

Figure 3 shows the mapping of the wakefield experienced by the witness bunch trailing the drive bunch in a collinear experiment [4]. Figure 4 illustrates the acceleration and deceleration of the witness beam in a TBA experiment, as measured by a magnetic spectrometer [5].

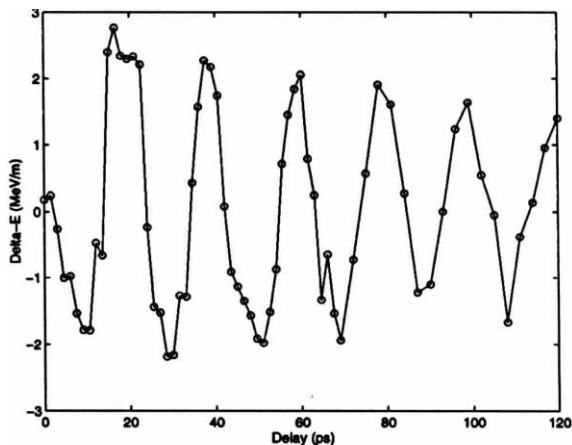


Figure 3: Witness beam energy measured as a function of the delay from the drive bunch.

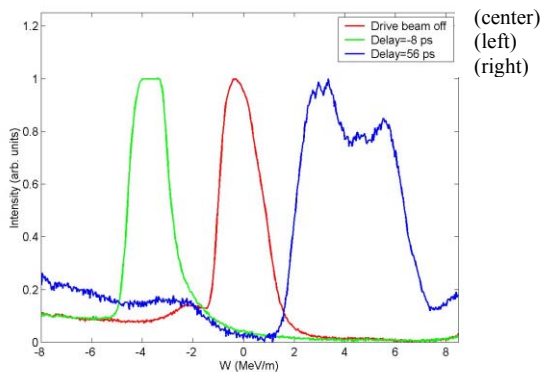


Figure 4: Projection of the witness beam image at the exit of the magnetic spectrometer.

Although the wakefield experiments at AWA were very successful in demonstrating the feasibility of the wakefield acceleration schemes, the achieved accelerating gradients were relatively modest, reaching only approximately 15 MV/m in the collinear configuration and 7 MV/m in the TBA experiments. The main factor limiting the achievable gradients was the quality of the drive beam; namely, the electron bunches were too long (20 to 40 ps FWHM) and their transverse emittance was too high ($> 1000 \pi$ mm-mrad). To address this problem, a new one-and-a-half-cell photocathode RF gun was built to eventually replace the original AWA drive gun, and a new beamline was constructed.

This new one-and-a-half cell drive 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 to 5 ps rms, and normalized emittances of 5 to 200 π mm mrad.

Due to the absence of a witness beam in this new test beamline, the experiments with dielectric wakefield structures focused on achieving high accelerating gradients in short standing-wave structures. Each structure consists of a cylindrical dielectric tube inserted into a cylindrical copper waveguide. 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. Thus, these experiments constitute breakdown threshold tests of the dielectric materials used so far: cordierite and quartz, with dielectric constants of 4.76 and 3.75, respectively. It is important to point out that the signal from the field probe is not used as a measurement of the fields present in the structure; these fields are calculated numerically by MAFIA given the geometry of the structure and the transmitted charge. Table 1 lists the parameters of three cordierite structures tested recently. A

fourth structure, employing quartz, was also tested recently and has inner and outer diameters, and length, of respectively 3.8, 15.0, and 25.4 mm. It operates at a frequency of 8.6 GHz and produces a gradient of 1.33 MV/m per nC of charge.

Table 1: Parameters of Cordierite 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

Figure 5 shows the peak values (positive and negative) of the wakefields measured by the field probe on Structure 1 for various bunch charges. As expected, the amplitude of the wakefields rises linearly with bunch charge. MAFIA simulations show that a 46 nC electron bunch traversing this structure generates a peak axial electric field of 21 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 6 shows the field probe signal for each bunch alone and also for the two bunches together.

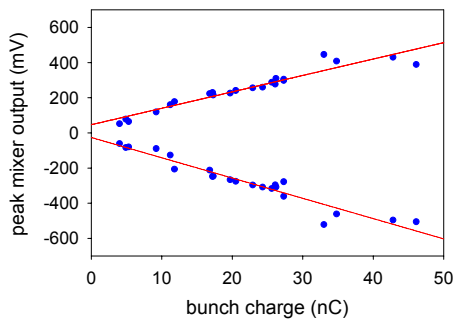


Figure 5: Peak values of the field probe signal plotted as a function of the charge in the drive bunch.

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 $TM_{0,12}$, $TM_{0,13}$, $TM_{0,14}$, and the dipole modes $HEM_{1,11}$ and $HEM_{1,12}$. 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 7 compares the FFT of the measured

radial electric field with the results from MAFIA simulations, identifying the main modes.

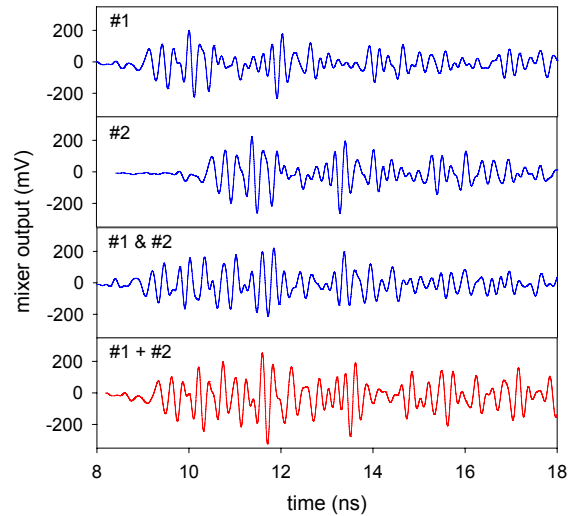


Figure 6: Field probe signal from: (a) bunch #1 alone; (b) bunch #2 alone; (c) bunches #1 and #2 separated by 1.5 ns (two RF periods of the klystron frequency); (d) numerical addition of the signals from (a) and (b), which is not strictly the correct approach, since the relative phases of these two signals 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.

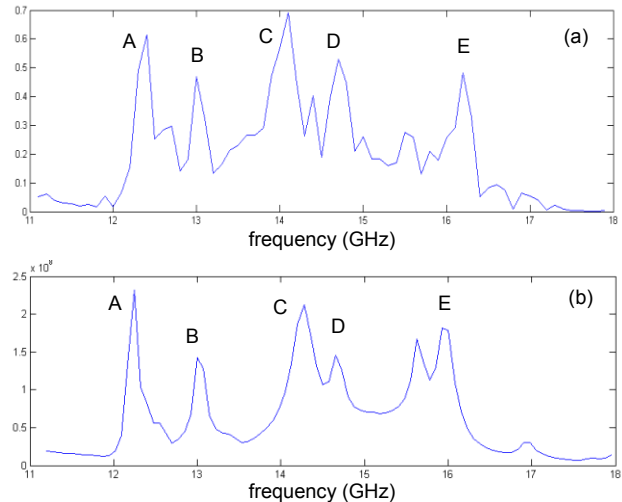


Figure 7: FFT of the radial component of the electric field (in arbitrary units), identifying the peaks A, B, C, D, E, respectively, as the modes $HEM_{1,11}$, $TM_{0,12}$, $TM_{0,13}$, $HEM_{1,12}$, $TM_{0,14}$: (a) measurement; (b) MAFIA simulation, taking into account the measured Q factor of each mode.

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 78 MV/m were reached. The temporal profile of the radial electric

field (E_r), as measured by the field probe, is shown in Fig. 8; also shown is its FFT.

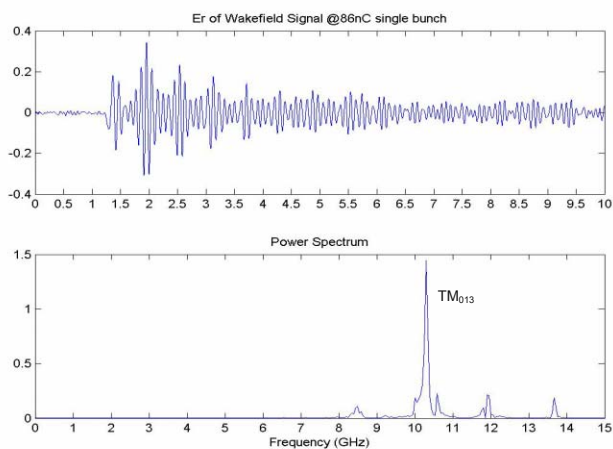


Figure 8: Measurement of the radial electric field driven by an 86 nC electron bunch, using the field probe on Structure 3: (a) temporal profile of the radial electric field; (b) the FFT of the signal.

The fourth structure recently tested was built with a quartz tube of considerably smaller inner diameter, and thus, even with a smaller transmitted bunch charge of 75 nC, reached the long-awaited gradient of 100 MV/m. Figure 9 shows the field probe signal and its FFT.

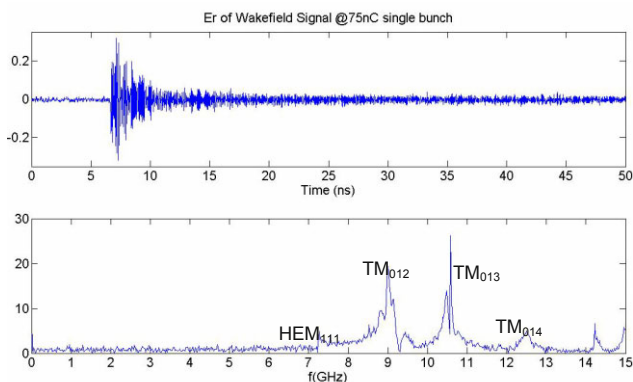


Figure 9: Measurement of the radial electric field driven by a 75 nC electron bunch, using the field probe on Structure 4: (a) temporal profile of the radial electric field; (b) the FFT of the signal.

EXPERIMENTS EXPLORING SUPERPOSITION

The experiments described in the previous sections can obviously benefit from having drive bunch trains instead of single drive bunches. The superposition of the wakefields can certainly lead to longer RF pulses and higher amplitudes, as shown in Fig. 6. Several experiments have aimed at going a step further, trying to explore more subtle aspects of superposition of fields and waveguide modes [6-8].

W-band dielectric loaded structures have been built and tested using the NLCTA electron bunch trains at SLAC [9]. These planar dielectric structures were constructed by inserting two alumina slabs into a rectangular waveguide section. The transverse dimensions of the structures are of the order of hundreds of micrometers, with a 720 μm gap for the passage of the 300 MeV electron beam. One of these devices was configured in a ring resonator circuit, where the measurements indicated that 200 kW of circulating power generated an accelerating field of 20 MV/m.

One of the more recent experiments [10] succeeded in reaching a transformer ratio slightly higher than 2, by using two properly spaced electron bunches of unequal charge. The transformer ratio is defined as the ratio of the maximum energy gain of the witness bunch to the maximum energy loss of the drive bunches. A bunch train with increasingly higher bunch charges (with predefined charge ratios), in which the bunches are placed in the accelerating phase of the previous bunch's wakefields, can achieve transformer ratio much higher than 2.

Another recent experiment using a bunch train aims at generating a long RF pulse, which in the future would be coupled into a second dielectric loaded structure, in a two-beam-accelerator configuration [11].

ULTRA-HIGH GRADIENTS AT THz FREQUENCIES

A recent experiment [12] employed the extraordinary SLAC FFTB electron beam to excite multi GV/m gradients in short fused silica capillary tubes. The 30 GeV electron beam with bunch charge of 3 nC traversed 1 cm long capillary tubes of inner diameter 100 and 200 μm . By changing the length of the electron bunches, the amplitude of the excited wakefields could be varied, while being monitored for signs of electric breakdown.

Peak accelerating fields of 12 GV/m and peak surface fields of 22 GV/m are believed to have been reached, however, preliminary data analysis indicates that the onset of breakdown may have occurred at approximately half these field values. It remains to be determined if breakdown was due to failure of the fused silica or simply by the vaporization of the metallic layer on the outer surface of the dielectric.

FUTURE EXPERIMENTS

The Argonne group is proceeding with upgrades at the AWA facility, implementing the fabrication of cesium telluride photocathodes that will make possible the generation of long drive bunch trains. They are also completing the fabrication of a new RF gun to generate the witness beam, and adding a second L-band klystron to the facility. These upgrades will enable the group to further explore the capabilities of dielectric loaded wakefield structures, both in the collinear and in the TBA configurations. The higher beam energy will facilitate propagation along longer structures, and the longer high

charge bunch trains will enable the generation of longer RF pulses.

The Yale/Omega-P/Columbia/Kharkov collaboration is proposing a dielectric loaded structure with a novel planar configuration, having two parallel channels, and thus allowing the RF power to be continuously coupled from the drive channel to the acceleration channel. Advantages of this configuration would be an expected high transformer ratio, and a simplified manner to transfer power between the two beams.

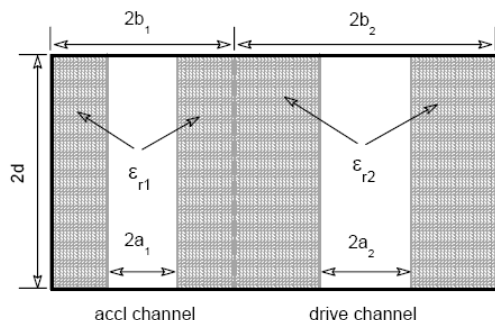


Figure 10: Cross section of the proposed two-channel dielectric wakefield accelerator.

There is a proposal to give continuity to the SLAC/FFTB wakefield experiments at the soon-to-be-commissioned SABER facility. The goals would be to explore in more detail the breakdown phenomena, to map the parameter space, and also to use coherent Cerenkov radiation as a diagnostic tool.

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