Advanced Accelerating Structures and Their Interaction with Electron Beams

Wei Gai

High Energy Physics Division, Argonne National Laboratory, Argonne, IL 60439

Abstract. In this paper, we give a brief description of several advanced accelerating structures, such as dielectric loaded waveguides, photonic band gap, metamaterials and improved iris-loaded cavities. We describe wakefields generated by passing high current electron beams through these structures, and applications of wakefields to advanced accelerator schemes. One of the keys to success for high gradient wakefield acceleration is to develop high current drive beam sources. As an example, the high current RF photo injector at the Argonne Wakefield Accelerator, passed a ~ 80 nC electron beam through a high gradient dielectric loaded structure to achieve a 100 MV/m gradient. We will summarize recent related experiments on beam-structure interactions and also discuss high current electron beam generation and propagation and their applications to wakefield acceleration.

Keywords: Enter Keywords here. Advanced structures, beams, wakefield
PACS: 41.20.-q , 41.75.Lx, 29.20.Ej

INTRODUCTION

For future high energy linear colliders beyond ILC/CLIC, accelerating structures in these machines will require: high accelerating gradient (~hundreds of MV/m), currently limited by material breakdown effects; high impedance (R/Q) for acceleration efficiency; sufficient higher order mode damping to control bunch to bunch beam breakup; the capability of accelerating positrons, which requires that the accelerating field be linear, etc. Along with structures, one also needs to develop high power RF sources to power them, typically at a level of ~ GW peak power to attain a few hundred MV/m. Achieving all the requirements at the same time is challenging, but there is an ongoing effort in the US to address these issues. Currently, there are several advanced structures under development: improved iris loaded structures, both traveling and standing wave [1]; dielectric loaded structures [2]; photonic band gap structures [3] and metamaterial structures [4]. There are two ways to power these structures: externally coupled high RF power and direct beam excitation or wakefield generation. In this paper, we discuss electron beam interactions with these structures and their implications to generation of high gradients.

CP1086, *Advanced Accelerator Concepts: 13th Workshop,* edited by C. B. Schroeder, W. Leemans, and E. Esarey

BEAM-STRUCTURE INTERACTIONS

When a beam passes through a structure with aperture 2a (shown in Figure 1) it loses energy and leaves a wakefield behind given by

$$E_z(z) = q\sum_n K_n \cos(k_{zn} z) \qquad (1)$$

where K_n is defined as a loss factor and depends on the aperture, bunch length, and wavelength as

$$K_n \rightarrow \frac{1}{a^2}\ \exp\left[-2\left(\frac{\pi\,\sigma_z}{\lambda_n}\right)^2\right]. \qquad (2)$$

As a general rule the wakefield gradient is ~ 0.5 MV/m/nC for a ~ 5 mm.

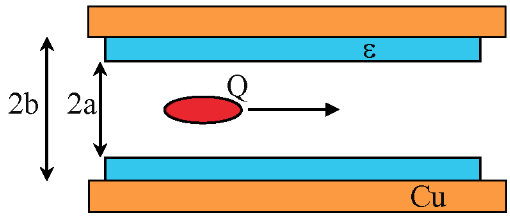


FIGURE 1. Diagram of a dielectric based structure. When a beam passes through the structure, a wakefield is produced and left behind by the drive beam Q. Similar wakefields are produced if one replaces the dielectrics by a set of periodic irises.

From the equations (1) and (2), the requirement for exciting larger wakefields is higher charge, short bunch length (a small fraction of the excited wakefield wavelength), and a small structure (and thus smaller beam to pass through the vacuum channel). These strong wakefields can be used for collinear wakefield acceleration, which we will discuss later. However, transverse wakefields (excited when the beam is not perfectly aligned on the axis of the structure) are proportional to a^{-3}; this term normally leads to severe beam break up of the both drive beam and accelerated beam if not properly controlled. For readily available drive beams and practical approaches to future colliders, with overall optimization, one needs to work in the frequency range of 10 – 100 GHz (i.e. cm – mm wavelengths). Another important feature for wakefield generation in structure is that the wakefield is in the form of pure electromagnetic wave in a waveguide and thus can be used for either collinear wakefield acceleration or extracted to another accelerating structure, such as in two beam acceleration.

In general, any slow wave structure can be used for wakefield acceleration. For illustration purposes, here we will use the dielectric based wakefield scheme as example. As an accelerating structure, the dielectric structure has certain advantageous properties that make it attractive as an alternative to conventional iris loaded copper structures: comparable accelerating properties to metal structures; more material options; possibly higher gradients; simpler geometry that is easy to construct and HOM damping [5].

Photonic bandgap structures are also a very attractive option because it is easy to damp higher order modes and they also have similar accelerating properties to iris loaded structures.

HIGH FIELD BEAM EXCITATION EXPERIMENTS

To facilitate high gradient wakefield experiments, we have constructed an RF photocathode based high current electron beam facility (Argonne Wakefield Accelerator or AWA). Currently, the facility consists of a 1½ cell L-band RF photocathode and L –band standing wave linac. Beam parameters that have been achieved are (1) single bunch operation: Q = 1-150 nC, 2-2.5 mm bunch length (rms), beam energy of 15 MeV, normalized rms beam emittance < 200 mm mrad (at 100 nC), with beam peak current ~10 kA; (2) bunch train operation: 4 - 16 bunches x 20 - 5 nC (current). The bunch charge and number limitation are due to the quantum efficiency of our Mg photocathode material.

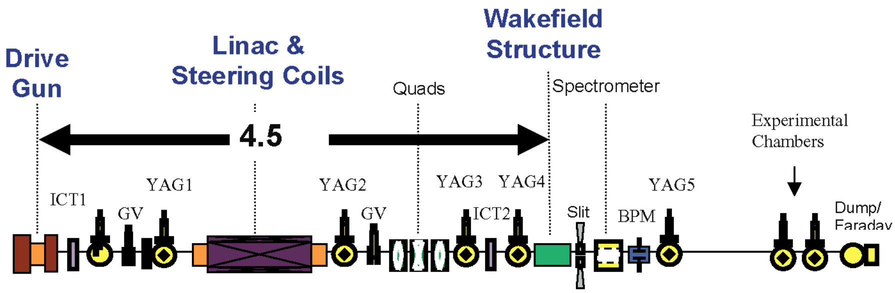


FIGURE 2. Schematic diagram of the Argonne Wakefield Accelerator.

High Gradient Wakefield Excitation in Dielectric Structure

After the AWA demonstrated its capability of producing > 100 nC per single bunch, attempts were made to achieve high accelerating gradients in several short standing-wave structures using wakefields from the high charge beam [6]. Each test structure consisted 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 near the outer diameter of the dielectric cylinder served to monitor the wakefields generated by the driving electron bunches, and to verify the absence of dielectric breakdown. These experiments constitute breakdown threshold tests. The dielectric materials used so far are cordierite and quartz, with dielectric constants of 4.76 and 3.75, respectively. These fields are calculated numerically by MAFIA given the geometry of the structure and the transmitted charge. We have been able to gradually increase the gradient from 20 MV/m a few years ago to the current

100 MV/m. The excited wakefield in the structure generally lasts about a few ns as shown in Figure 3. The results show no observed breakdown.

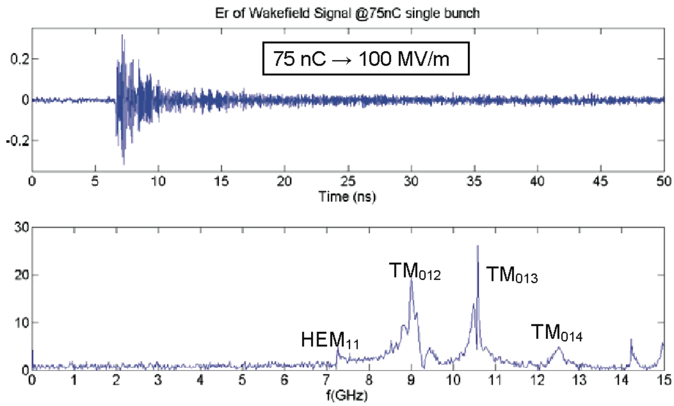


FIGURE 3. Illustration of high gradient generated in a dielectric tube by a high charge beam. The data indicates that 100 MV/m produced inside the structure.

High Power RF Generation in Dielectric Based Structures

Power extraction using a dielectric-loaded (DL) waveguide is a way to generate high power rf waves for future particle accelerators, especially for two beam acceleration (TBA). In TBA, a drive particle beam travels through a decelerator, where the beam power is partially transferred to the trailing wakefield. Then with a properly designed rf output coupler, the power generated in the decelerator is extracted to accelerate another beam [7]. The decelerator, together with the rf output coupler, is called a power extractor.

Power extraction with DL waveguides is a promising approach for future high power rf source development. At AWA, a 7.8GHz power extractor using a circular DL waveguide has been designed and tested with single electron bunches and bunch trains. 30MW of power has been reached in single bunch tests, and 44MW in 4 bunch train tests. Also 10ns and 22ns rf pulses have been generated with bunch trains, but at lower power level (~ MW).

The power level is limited by beam current, i.e. the quantum efficiency (QE) of the present magnesium photocathode. We are developing a new cesium telluride photocathode with a much higher QE. We expect to be able to generate 10ns and 22ns rf pulses with power levels on the order of 100MW once this new cathode is completed installed.

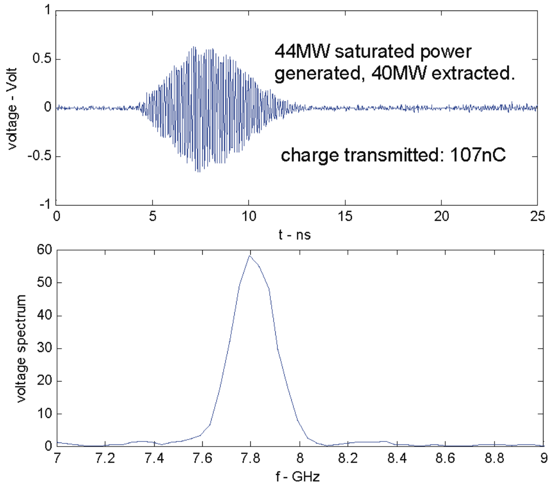


FIGURE 4. 7.8 GHz high power generation in a dielectric tube with a high charge 4 bunch train. The top plot shows the extracted power in time domain and the bottom is the corresponding power spectrum.

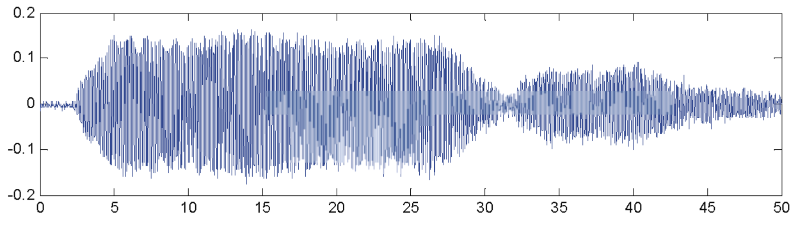


FIGURE 5. Measured RF generation for 16 pulses separated by 1.56 ns, with total the pulse length 20 ns.

Wakefield Experiments using Metallic Structures

Recently, we have performed an experiment the AWA using a standing wave X-band structure developed at SLAC [8]. The experimental set up is the same as the high gradient dielectric experiment. The structure is shown in Figure 6a. The measured wakefield is shown in Figure 6b. The estimated peak wakefield generated here is about 50 MV/m for 80 nC drive beam. From the figure, we have estimated that the loaded Q for the cavity is about 5400. One could simply increase the gradient to much higher level by using a multiple drive beam as discussed before. We believe this is an effective way to test the properties of high gradient structures and higher order mode excitations.

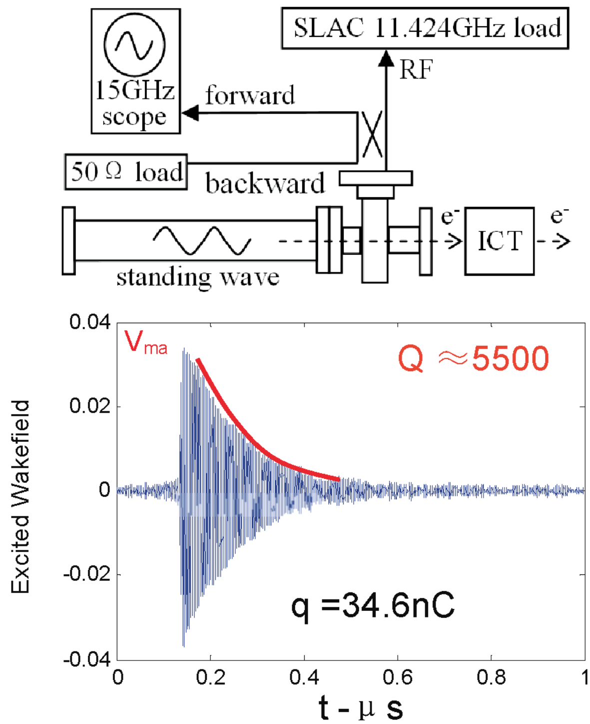
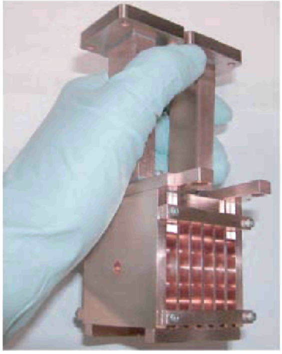


FIGURE 6. X-band SLAC structure wakefield experiment. (a) schematic of the experimental set up; (b) measured wakefield.

At the MIT beam laboratory, they have conducted a beam excited wakefield experiment in a 17 GHz photonic band gap structure [9]. This structure had been previously conditioned to 35 MV/m. In this experiment, a 17 MeV bunch train resonantly excited the wakefield in the structure. The wakes were then taken out from the rf coupling port for diagnostics. Figure 7 shows the results; a detailed analysis showed the data to be in good agreement with simulations.



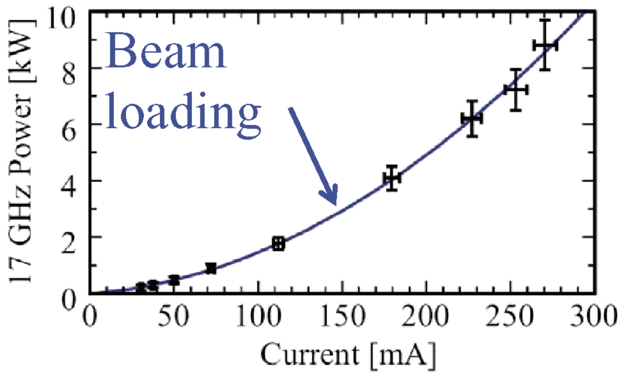


FIGURE 7. Experimental test of the MIT 17 GHz photonic band gap structure. The structure was excited by a train of electron bunches and power extracted from the coupling ports. The data (crosses) and simulation (solid curve) agree well.

High Transformer Ratio Experiments

In this section, we discuss another class of wakefield experiments: high transformer ratio wakefield acceleration. In a wakefield accelerator, the fields generated by a leading, high-charge *drive* bunch (either a single drive bunch or a train of drive bunches) are used to accelerate a trailing, low-charge *witness* bunch. An important parameter that influences the performance of a wakefield accelerator is the transformer ratio R=(maximum energy gain of the witness bunch)/(maximum energy loss of the drive bunch). However, in a collinear wakefield scheme, if the drive beam distribution is symmetric the maximum accelerating field can not exceed twice the deceleration field in the drive beam. This is so called transformer ratio limitation. To accelerate the witness beam to high energy, it is desirable to make R as large as possible. One way to achieve a higher transformer ratio is to use a ramped bunch train with the proper charge ratio and spacing between bunches. An experiment was performed at the AWA a few years ago, using two drive bunches with a charge ratio of 2.5, where they demonstrated a transformer ratio > 2.3 by accelerating a very low charge witness beam [10].

Another way to enhance the transformer ratio is to use a structure in which the drive beam and witness beam pass through different sections of the wakefield structure. This type of scheme takes advantage of the impedance difference at different structure transverse location. As recently proposed by Marshall and Hirshfield [11], Figure 8a shows a schematic of a cavity in which the drive beam passes through a larger aperture in the cavity than the witness beam.

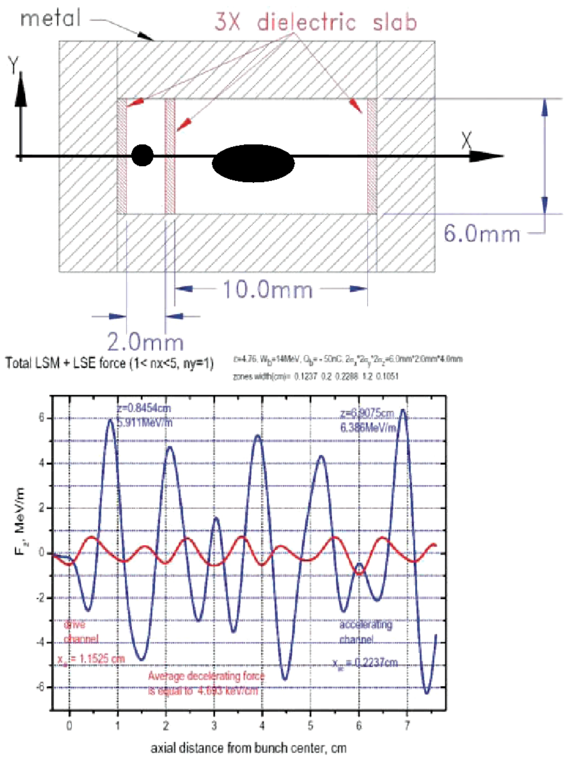


FIGURE 8. (a) Schematic of high transformer ratio cavity using the principle of drive and witness beams traversing different paths through the structure. (b) Simulation results showing the transformer ratio enhancement.

Other Wakefield Experiments

In addition to the beam-structure experiments already discussed, I will briefly mention two others. Details of these experiments can be found in the references.

1. THz Fiber Wakefield Generation using SLAC FFTB Beam by a team from ULCA (12). The 30 GeV small and short beam generated a wakefield in a quartz tube yielding gradients on the order of 2 – 4 GV/m in the THz range.
2. 21 GHz Dielectric Power Extraction Experiments. This is a collaboration involving DULY Research, ANL, and the CLIC Test Facility. An attempt was made using a 21 GHz dielectric structure to demonstrate power extraction concepts. [13] A reasonable level of generated power was measured.

ACKNOWLEDGMENTS

I would like to thank my colleagues at ANL, SLAC, MIT and Yale/Omega-p/Columbia for providing the materials on their experiments. This work is supported by the US Department of Energy.

REFERENCES

1. S. G. Tantawi, and V. A. Dolgashev, "Summary Report of Working Group 2: High-Gradient Structures", in 12th Advanced Accelerator Concepts Workshop, edited by M. E. Conde et al., AIP Conference Proceedings 877, American Institute of Physics, Melville, NY 2006., pp. 139- 146.
2. Evgenya I. Smirnova, Amit S. Kesar, Ivan Mastovsky, Michael A. Shapiro, and Richard J. Temkin, Phys. Rev. Lett. **95**, 074801 (2005)
3. R. Keinigs, M. E. Jones, and W. Gai, Part. Accel. **24,** 223, (1989).
4. S. Antipov, L. Spentzouris, W. Gai, M. Conde, F. Franchini, R. Konecny, W. Liu, J. G. Power, Z. Yusof, and C. Jing, Appl. Phys. 104, 014901, July (2008).
5. P. Zou et al, Review of Scientific Instruments, **71,** No.6, (2000).
6. M. E. Conde, "Survey of Advanced Dielectric Wakefield Accelerators", in *2007 Particle Accelerator Conference, p. 1899-1903.*
7. F. Gao et al, Phys. Rev. ST-AB 11, 041301(2008).
8. S. Tantawi, V. Dolgashev (private commnunication)
9. . Marsh et al., in this proceedings.
10. C. Jing, et al, Phys. Rev. Lett. 98, 144801 (2007)
11. Hirshfield, et al., in this proceedings.
12. M. C. Thompson, et al., Phys. Rev. Lett. **100**, 214801 (2008)
13. D. Newsham, et al., "Construction and Testing of a 21 GHz Ceramic Based Power Extractor", in *2003 Particle Accelerator Conference*, p 1157-1159