High power radio frequency generation by relativistic beams in dielectric structures

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We have studied the interaction of a high current electron beam with dielectric loaded waveguides as a source of electromagnetic radiation. A unique high current photoinjector-based electron linac was used to generate the drive beam for these experiments, and the fields generated were diagnosed using a trailing probe (witness) beam from a second photocathode gun. Traveling wave dielectric structures with luminal ($v_{\mathrm{phase}}=c$) frequencies of 15 and 20 GHz were used. The radio frequency power levels generated in these initial experiments were very large—up to 11 MW.
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I. INTRODUCTION

Research on the applications of high frequency dielectric loaded radio frequency (rf) structures in accelerator physics has been proceeding for some time, primarily for wakefield accelerators, where rf electromagnetic fields generated by an intense drive beam passing through a slow wave structure are used to accelerate a second beam to high energy.[1] In the last 10 years, the availability of rf photocathode based electron source technology for generating high current beams and the advent of high dielectric constant low-loss materials provide an additional impetus to the study of dielectric devices as both accelerating cavities and slow wave structures for rf generation.[2]

The physics of the interaction of a beam with a dielectric structure is as follows. An intense relativistic ($v\approx c$) electron beam passing through a dielectric tube with inner radius a, outer radius b and dielectric constant ϵ will emit Cherenkov radiation.[3] Unlike the case of an unbounded medium, the radiation will drive only the allowed modes of the structure. The beam induced field is referred to as its *wakefield*. The wakefield is dominated by the TM_{0n} modes if the beam is on axis. The radiation generated will have a phase velocity equal to the beam velocity and a group velocity $\approx c/\epsilon$. The axial electric field is given by,[4]

$$E_z(r,z,t)=Q\sum_n E_{zn}(r,\omega_n,a,b,\epsilon)\cos(\omega_n t-k_n z)\times\exp(-(k_n\sigma)^2/2) \tag{1}$$

where Q is the total charge in the beam, σ is the rms bunch length of the drive beam (assumed Gaussian), ω_n is the frequency of the mode, k_n is the wave number of the mode, and n is the mode number.

If the bunch length is comparable with the wavelength of the fundamental ($n=1$) mode, then all higher order mode contributions can be neglected. (This will turn out to be the case for the experiments described in this article.) The analytic expression for E_{zn} and the dispersion relation for k_n and ω_n are derived in Ref. 4. All other field components, energy density, etc. can be derived directly from Eq. (1). The radio frequency power P generated can be expressed as

$$P=v_g U, \tag{2}$$

where U is the energy density per unit length in the structure and v_g is the group velocity of the radiation.

These devices possess some obvious advantages:

(i) Simplicity of fabrication. The structure is a glass or ceramic tube inserted into a conductive jacket.
(ii) Parasitic wake control and suppression. Wakefield acceleration techniques requiring the transport of intense drive beams suffer from beam losses caused by hybrid modes generated by off-axis injection errors. The hybrid electromagnetic (HEM_{11}) mode is generally lower in frequency than the transverse magnetic (TM_{01}) accelerating mode,[4] providing greater tolerance to the beam breakup instability than conventional structure based accelerators. Multibunch beam breakup effects can also be controlled with a simple mode suppression scheme.[5]

The rf power generated in these devices can be very large. Although the research described here is oriented toward the development of high energy particle accelerators, the rf generated by beam-driven dielectric structures may also have applications in other areas requiring high frequency rf sources.

There are also potential difficulties with dielectric devices which must be understood and dealt with in order for this technology to be useful for high energy accelerators:

(a) Breakdown limits at high fields. The dielectrics used in the wakefield structures must be able to reliably hold off the large electric fields without surface or volume flashover.
(b) Charging from intercepted beam halo. The generation of large static electric fields from halo and missteered beam electrons deposited in the dielectric can deflect subsequent bunches resulting in loss of beam.
(c) Radiation damage effects on dielectric properties. The materials used must not change their dielectric constant

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while being irradiated in the beamline. This is especially important for the transformer devices described in Sec. II, since the fundamental frequencies of the two sections must match closely.

Early experiments on wakefield acceleration in dielectric devices concentrated on proof of principle experiments in the low-field regime (field amplitudes ≈0.1 MV/m). In particular our previous work[6] emphasized understanding the underlying physics such as the mode structure of the generated wakefields and comparison of measurements with theory and simulations. Since then, efforts have been concentrated on measurements of dielectric wakefield structures at high gradients with the emphasis on developing techniques useful for high energy accelerators. However, one of the key components of a practical wakefield accelerator is the source of high charge, short electron bunches. The Argonne Wakefield Accelerator (AWA)[7] was designed and constructed to develop this technology. Currently, the AWA is capable of generating 10–100 nC beams with pulse lengths of 10–40 ps full width at half maximum (FWHM). In this paper, we report the results of our initial high-gradient experiments on collinear drive-witness beam geometry dielectric structures.

II. DIELECTRIC WAKEFIELD DEVICES AS RF SOURCES

Future linear colliders for high energy physics will require high frequency rf power sources. At the same time, conventional rf power technology based on klystrons is reaching its limits, and will probably be difficult to implement beyond *X* band (11.4 GHz).[8] Dielectric wakefield structures driven by the short intense beams produced by modern photocathode sources offer the potential for fulfilling future requirements for cm and mm wave rf source applications.

The technique is adaptable to a two-beam (transformer) configuration,[9] in which the wake generated by multiple drive bunches in one dielectric structure is coupled into a second structure with the same fundamental frequency but smaller transverse dimensions and group velocity. This provides a transformer ratio enhancement of the accelerating fields as well as simplifying the staging of the drive and witness beams (see Fig. 1). We have identified dielectric transformer devices as offering the greatest promise for the application of wakefield acceleration to high energy acceleration.

In view of the challenges described in Sec. I, the experiments have been designed to investigate key aspects of the technology separately. In this article we report only on the generation of rf fields in stage I by the high current drive beam. The wakefields were diagnosed by passing the witness beam through stage I collinearly with the drive beam rather than through a parallel accelerating section. Future experiments will deal with the issues of rf coupling between the stages of the transformer and measurements of acceleration of the witness beam in stage II.

The duration of the rf pulse produced by a single drive bunch is limited by the length of the dielectric structure and the dynamics of the beam to ≈1–4 ns but can be easily increased by using multiple drive pulses. Using photoinjector technology, a train of drive bunches can be produced by optically splitting the laser pulse and delaying each micropulse to arrive at the photocathode separated by an integer multiple of one gun rf period nT_{rf}. With the length of the dielectric structure adjusted to be cnT_{rf} the rf pulse length produced will then be equal to the duration of the laser bunch train.

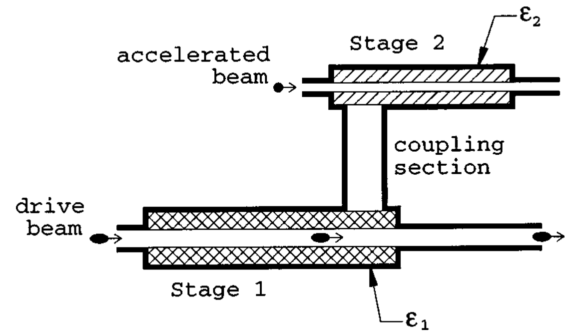

FIG. 1. Schematic diagram of the dielectric step-up transformer currently under development. The rf generated by the drive beam is coupled into a second dielectric structure. The dielectric constants ϵ_1 and ϵ_2 and the drive and accelerating stage geometries are chosen to provide both longitudinal and transverse compression of the rf pulse in the accelerating stage, while at the same time maintaining the same TM_{01} frequency in each stage. The measurements reported in this paper are of the wakefields in the first stage only, diagnosed by also passing the witness beam through the drive structure.

III. WAKEFIELD MEASUREMENT SYSTEM

While the wakefield in a structure may be measured at a single point using a probe, a more satisfactory method for globally studying wakefields is the witness beam technique[10] in which a second relativistic beam is used to diagnose the fields excited by the drive beam. In this case what is measured is the *wake potential*,

$$W_z(s) = e\int E_z[z, t=(s+z)/c]\,dz,$$

where s is the longitudinal separation of the two beams, and the integral is taken along the path traversed by the beams through the structure. Both beams are relativistic so that relative phase slip of the beams can be neglected. The measurements discussed in this paper correspond to direct measurements of the wake potential using a probe or *witness* beam; the delay (s/c) is continuously adjustable.

The Argonne Wakefield Accelerator facility consists of a high current photoinjector and linac which generates a 14 MeV drive beam, a second high brightness 3.9 MeV photoinjector which produces the witness beam, beamlines to transport drive and witness beams through the wakefield device under test, and a magnetic spectrometer to measure the change in energy of the witness beam from the wakefield of the drive beam. A schematic view of the AWA is shown in Fig. 2.

The drive and witness guns share a common laser system. A portion of the laser pulse is split off and directed through an optical trombone before being transported to the witness gun to adjust the delay between the two beams.[11] At

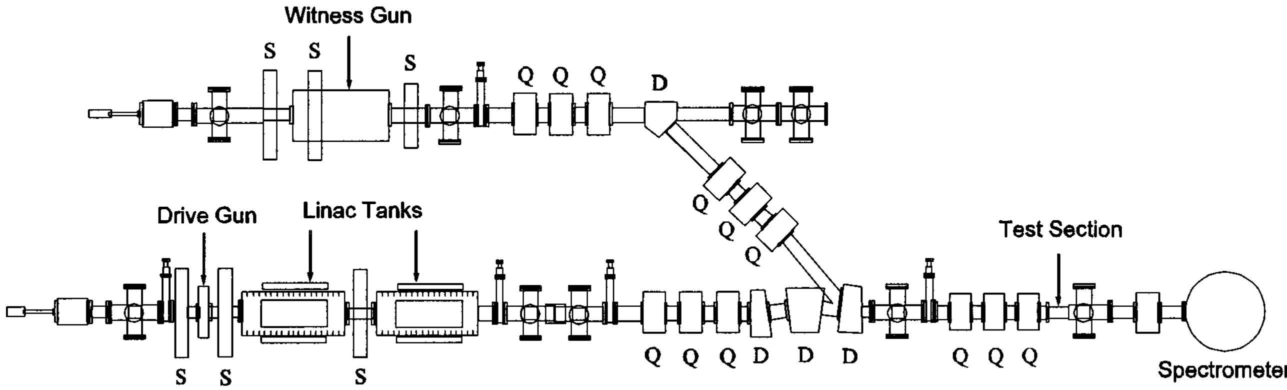

FIG. 2. Schematic of the AWA experimental setup; S, Q, and D indicate solenoids, quadrupoles, and dipoles, respectively.

the same time the phase of the rf driving the witness gun is varied to maintain a constant laser injection phase. The witness beam is detected at the 60° port of the spectrometer using a phosphor screen and intensified closed circuit television (CCTV) camera.

The drive beam intensity is monitored using an integrating current transformer immediately upstream of the test section. The amplitude of the generated wakefield is also sensitive to the length of the drive beam, which in turn is a function of the drive linac tune. A bunch length monitoring system was incorporated using an aerogel Cherenkov radiator which can be inserted into the beamline. Light produced in the radiator is then transported to a streak camera. (This system was not in place for the initial 15 GHz device measurements reported below; thus, the bunch lengths quoted are estimates based on comparisons of the measurements with numerical calculations.)

IV. DIELECTRIC DEVICE MEASUREMENTS

As part of the initial facility testing, we used the simplest beam and dielectric structure geometry, with the drive and witness beams passing collinearly through the structure under test. This configuration was not expected to produce high accelerating gradients but was convenient for system validation. The dielectric devices were fabricated from borosilicate glass which has a dielectric constant ≈4 and is known from previous measurements to be sufficiently conductive so that any intercepted charge (from beam halo, missteering, etc.) is not accumulated.

A. 15 GHz device delay scan

The wake potential for a 15 GHz structure (inner radius $a=5$ mm, outer radius $b=7.7$ mm, length=11 cm) was mapped out in detail. Due to limitations of the beamline for this measurement only a modest drive beam charge (11 nC/pulse) could be transmitted. The bunch length was not measured but was estimated to be about 15 ps rms. The witness gun delay was increased in 5 ps steps (later in the run the delay increment was changed to 10 ps increments) from 0 to 400 ps. The image of the witness beam spot on the phosphor screen downstream of the spectrometer was digitized at each delay setting and saved to disk for offline analysis.

Figure 3 shows the wake potential as measured from the energy change of the centroid of the witness beam as a function of the delay. The largest energy shift of the centroid is ≈2.5 MeV/m. Because the 2.5 mm rms length of the witness beam is a significant fraction of the wavelength of the wakefield, the actual gradient is larger than the gradient measured from the witness beam centroid change in energy. By comparing the data with the numerical simulation convolved with a Gaussian witness bunch shape, a true gradient of ≈3.6 MeV/m is inferred.

Additional optimization of the laser injection phase and beamline magnet settings resulted in a gradient of approximately 6 MeV/m with 20 nC drive beam intensity. This agrees well with calculations assuming an rms drive bunch length $\sigma_z=2.5$ mm (8.3 ps), and later verified by bunch length measurements using the same machine parameters.

The rf power generated by the beam was also determined indirectly by using the measured gradient to normalize the analytic expressions for the dielectric wakefields[4] and computing the power flow through the structure. Equation (2) shows that a modest gradient in a high group velocity structure (in this case $v_g \approx 0.3c$) can correspond to a very

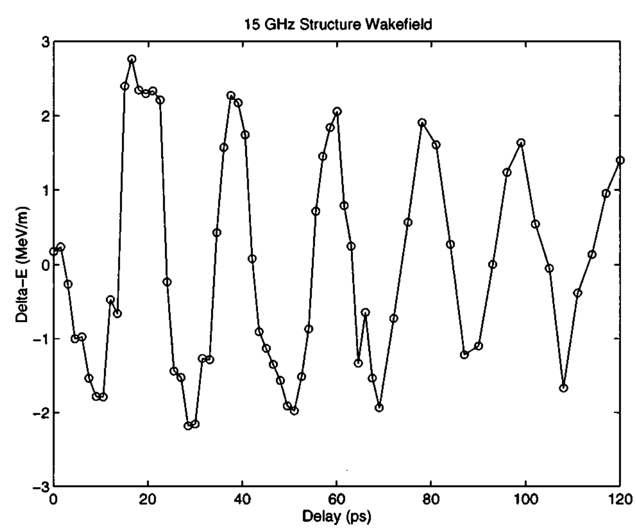

FIG. 3. Wake potential measurement for 15 GHz dielectric structure. Each data point is the change in the bend view centroid of the witness beam at the spectrometer 60° port.

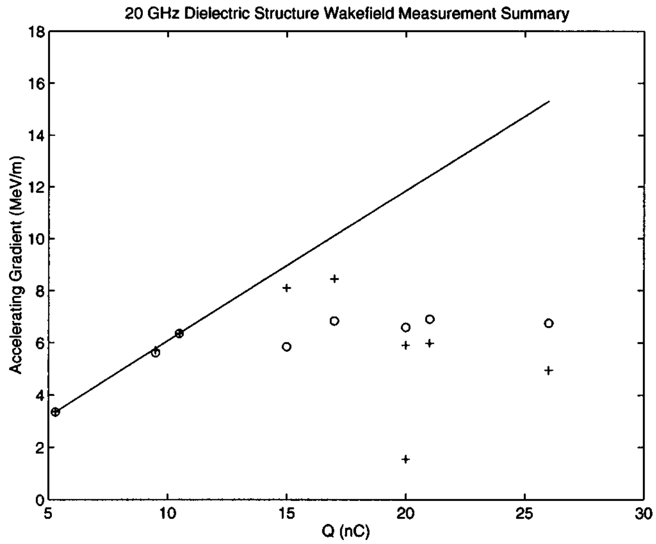

FIG. 4. Peak accelerating gradient vs drive beam charge in 20 GHz dielectric structure. Crosses: AWA measurements. The rolloff in the measured gradient to an asymptotic value of ≈6 MeV/m is due to drive bunch lengthening with increasing drive charge, as can be seen from the circles which show the predicted gradient based on the 10.5 nC point and on the measured bunch length at each charge. The straight line shows the predicted gradient based on the 10.5 nC measurement in the absence of further bunch lengthening.

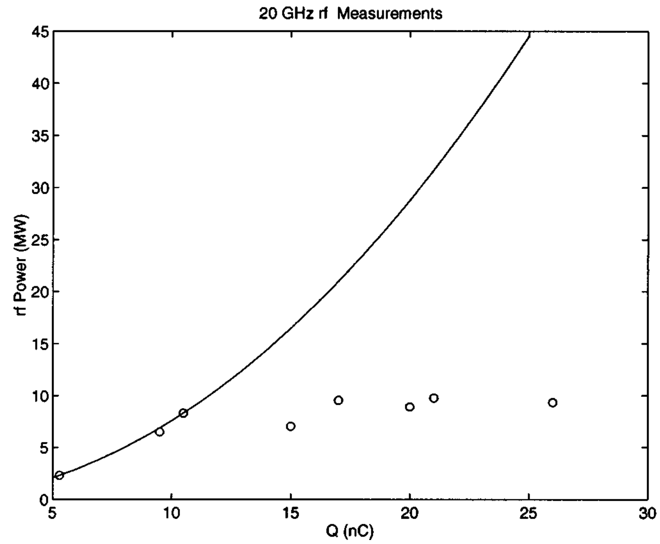

FIG. 5. Equivalent rf power levels for the data in Fig. 4. The solid line shows the extrapolated power based on the 10.5 nC measurement assuming no bunch lengthening with increasing charge.

large rf power. In this case the measured gradient of 6 MeV/m implies an rf power of 11 MW.

B. 20 GHz device—gradient vs drive charge and bunch length

In order to increase the transmission of the drive beam through high impedance wakefield devices, a quad triplet was located upstream of the wakefield device. The improved optics allowed up to 40 nC drive charge/pulse to be transmitted through a 3 mm radius aperture 10 cm in length. At these intensities background from x rays and secondary electrons from drive beam scraping caused problems for witness beam detection. After careful radiation shielding and with improved beam monitoring the background became manageable.

A 20 GHz device ($a=2.9$ mm, $b=5.0$ mm) was used to study wakefield effects as a function of drive beam intensity and length. The drive beam current was gradually increased by removing neutral density filters in the laser transport line for the drive gun. The beam transport lines were retuned to give maximum transmission for each drive beam intensity. At each point the gradient (witness beam energy centroid change) was measured, along with the drive bunch length and intensity.

Drive charges for this experiment were in the 5–25 nC/pulse range. rms drive bunch lengths were found to vary from 6 ps at 5 nC to 20 ps at 25 nC. This increase in bunch length resulted in a rolloff in the observed wakefield gradient with drive charge as shown in Fig. 4, resulting from the $\exp[-(k_n\sigma)^2/2)]$ term in Eq. (1).

This factor is proportional to the Fourier spectrum of the drive current and relates the magnitude of the wakefield to the bunch length. Figure 4 also shows the predicted gradient if the length of the drive bunch had remained constant at its 10.5 nC value (and thus scaled linearly with the beam charge), and also the predicted gradient based on beam charge and the expected $\exp(-k^2\sigma^2/2)$ scaling[4] with bunch length. In this latter case the scaled gradient generally reproduces the trend of the data indicating that the observed rolloff results from drive bunch lengthening.

The rf power generated is shown in Fig. 5. Correcting the 6.55 MeV/m gradient for the 2.5 mm witness bunch length gives a true gradient of 11.5 MeV/m corresponding to 11 MW rf power. The extrapolated power curve shows the potential of this technique for generating technologically interesting power levels. The main requirement for realizing higher power is to achieve shorter drive bunch lengths.

V. DISCUSSION AND SUMMARY

The Argonne Wakefield Accelerator provides a high charge and short electron pulse length source. This source has been used to demonstrate particle acceleration and rf generation by beam wakefields in dielectric structures, obtaining peak rf power levels in the 10 MW range. Although the absorbed radiation dose to the dielectrics was not monitored, no apparent change in the microwave properties of the structures was observed over several days of operation, despite sufficient intercepted beam to optically darken the dielectric tubes. During the experiment, no apparent charging of the dielectric was observed. No sign of breakdown (either surface or bulk) was found in these experiments. Despite a large intercepted beam from missteering during tuning and from beam halo, charging of the borosilicate glass dielectric was not found to be a problem. Wakefield acceleration in dielectric structures has been studied at gradients significantly higher by about a factor of 10 than demonstrated previously.[6] The high rf power levels generated suggest the potential application of this technology to the design of high frequency rf sources both for accelerator and other applications.

Attaining higher, technologically interesting gradients can be accomplished by two paths. Simply increasing the charge in the drive beam is difficult to accomplish at the present facility without increasing the bunch length but may be possible at an electron source optimized for this purpose. An attractive option is the use of step-up transformer structures to enhance the accelerating gradient in the second stage of a two-beam structure, which can be done even though the axial field in the first tube is relatively low. Further development of this technology is underway with the goal of demonstrating acceleration of the witness beam in the full two-stage device.

The measured efficiency of rf generation in these experiments is rather low; however, it is worth pointing out that this is due to the limitations of the present experimental setup rather than any intrinsic limitation on wakefield technology itself. These experiments were planned as proof-of-principle and thus have not been optimized for high efficiency.

In summary, the experiments with dielectric wakefield devices have been successful. High rf power has been generated at 15–20 GHz with no breakdown or other changes in dielectric properties observed. We foresee no limitations to extrapolating this technology to the 100 MW level with an optimized electron source. The results obtained here demonstrate that this technology is potentially useful for high power and high frequency rf sources.

ACKNOWLEDGMENT

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[1] R. Keinigs, M. Jones, and W. Gai, Part. Accel. **24**, 223 (1989).
[2] W. Gai, J. Simpson, and R. Konecny, in *Accelerator Science, Technology and Applications,* Proceedings of the 1997 IEEE Particle Accelerator Conference, Vancouver, Canada, May 12–16, 1997 (in press).
[3] P. A. Cherenkov, Dokl. Akad. Nauk SSSR **2**, 451 (1934); I. E. Tamm and I. M. Frank, *ibid.* **14**, 107 (1937).
[4] M. Rosing and W. Gai, Phys. Rev. D **42**, 1829 (1990).
[5] E. Chojnacki, W. Gai, C. Ho, R. Konecny, S. Mtingwa, J. Norem, M. Rosing, P. Schoessow, and J. Simpson, J. Appl. Phys. **69**, 6257 (1991).
[6] W. Gai, P. Schoessow, B. Cole, R. Konecny, J. Norem, J. Rosenzweig, and J. Simpson, Phys. Rev. Lett. **61**, 2756 (1988).
[7] W. Gai, M. Conde, G. Cox, R. Konecny, J. Power, P. Schoessow, J. Simpson, and N. Barov, *Advanced Accelerator Concepts, Lake Tahoe, CA, 1996*, edited by S. Chattopadhyay, J. McCullough, and P. Dahl, AIP Conference Proceedings No. 398 (American Institute of Physics, Woodbury, NY, 1996); M. E. Conde, W. Gai, R. Konecny, X. Li, J. Power, P. Schoessow, and N. Barov, J. Appl. Phys. (submitted).
[8] B. Danly, in *Advanced Accelerator Concepts, Fontana, WI, 1994*, edited by P. Schoessow, AIP Conference Proceedings No. 335 (American Institute of Physics, Woodbury, NY, 1994).
[9] E. Chojnacki, W. Gai, J. Simpson, and P. Schoessow, in *Accelerator Science and Technology*, Proceedings of the 1991 IEEE Particle Accelerator Conference, San Francisco, CA, May 6–9, edited by M. Allen (IEEE, Piscataway, 1991), pp. 2557–2559.
[10] H. Figueroa, W. Gai, R. Konecny, J. Norem, A. Ruggiero, P. Schoessow, and J. Simpson, Phys. Rev. Lett. **60**, 2144 (1988).
[11] J. Power and M. E. Conde, Rev. Sci. Instrum. **69**, 1295 (1998).