

# RESULTS FROM THE ARGONNE WAKEFIELD ACCELERATOR TEST FACILITY

W. Gai, M. Conde, R. Konencny, W. Liu, J. Power  
 High Energy Physics Division, Argonne National Laboratory  
 Argonne, IL 60439

*Abstract*

We report on the wakefield experimental results using the Argonne Wakefield Accelerator (AWA). Since the commissioning of the AWA, we have conducted numerous wakefield related experiments: plasma wakefield acceleration, dielectric collinear wakefield and step-up transformer two-beam acceleration experiments. In this paper, we summarize the experimental results and discuss the ongoing AWA upgrade to further these experimental results. Future plans for development of a 100 MeV demonstration accelerator based on wakefield method are presented.

## 1 INTRODUCTION

The Argonne wakefield accelerator, a high current photoinjector based electron accelerator, has been in operation for many years [1]. The AWA consists of a high current half cell L-band photo injector and a linac, which generates a 10 –100 nC, 35 ps (FWHM) single pulse, 15 MeV electron beam. A high brightness 3.9 MeV photoinjector produces a witness beam. Beamlines to transport the drive and witness beams through the wakefield device under test, and a magnetic spectrometer to measure the energy change of the witness beam from the wakefield of the drive beam. A schematic view of the AWA is shown in Figure 1.

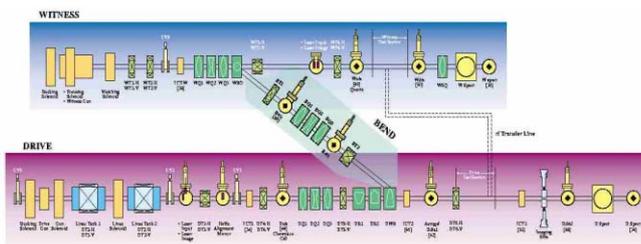


Figure 1: Schematic layout of the AWA facility and experimental setup. The witness beam can be steered into the lower test line for collinear wakefield experiments or upper line for two beam acceleration experiments. The distance between the drive and the witness beams can be adjusted using a laser trombone.

The AWA beam was systematically characterized and compared with PARMELA simulations [1]. The electron beam has been used for plasma wakefield acceleration [2], dielectric collinear wakefield [3] and step-up transformer two-beam acceleration experiments with great success. In addition, coherent Cherenkov and transition radiation

experiment in the microwave region were conducted for astrophysics applications [4]. In this paper, we give a summary of the dielectric wakefield experiments and discuss the ongoing AWA facility upgrade, which includes a new 1 ½ cell RF photoinjector and a new AWA laser system. This new photoinjector will produce an electron beam with 3 ps rms pulse length and 200 mm mrad normalized rms emittance for 100 nC beam. We are also planning to generate an electron pulse train (40 nC, 3 ps rms and 100 mm mrad normalized emittance and up to 64 pulses at 15 MeV). With this high current electron beam, we will be able to demonstrate 100 MeV acceleration in less than a meter in dielectric based accelerating structures, with potential applications to future high energy colliders. Also this electron beam can be used for studying many advanced acceleration topics such as nonlinear plasma wakefield, high power (>100 MW) high frequency (> 30 GHz) RF generation and wakefield excitations of different types of structures.

## 2 COLLINEAR WAKEFIELD EXPERIMENT RESULTS

### 2.1 Single Drive Beam Collinear Wakefield Experiments

The initial experiments were carried out using a single drive beam (~20 nC) to drive a dielectric wakefield tube with  $a=5\text{mm}$ ,  $b=7.7\text{ mm}$  and dielectric constant of 4. The highest peak acceleration field achieved was 11 MV/m in this experiment [3]. Further increasing the acceleration gradient is limited because the drive beam is rather long for high gradient wakefield excitation, also high emittance from the ½ cell gun limits the total charge transported through the structure, thus the peak gradient. However, it shows that the AWA performed as it was designed, and with improved drive beam quality, the gradient should go well beyond 100 MV/m. Figure 2 shows a dielectric wakefield experiment device and Figure 3 show a typical wakefield result from a single drive beam.



Figure 2: Collinear wakefield experiment setup. Where a high charge beam passing through a dielectric structure will generate high gradient and thus accelerator a trailing witness beam. The drive beam can be either a single or multiple bunches.

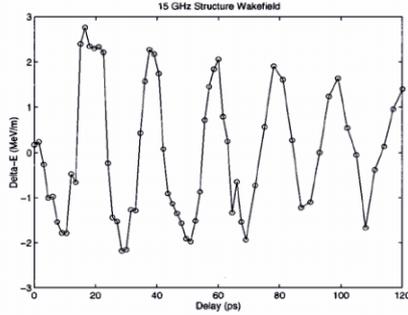


Figure 3: Wakefield measurement for 15 GHz dielectric structure. Each data point is the change in the bend view centroid of the witness beam at the spectrometer port.

### 2.2 Multimoded multi-drive beam wakefield experiment

A second type of collinear dielectric wakefield experiment was wakefield excitation in multimoded structures by a train of electron bunches. It is still a cylindrical dielectric tube as in Figure 2, but it has much larger outer radius  $b=14.4$  mm and much higher dielectric constant  $=38$ . The excited wakefield is dominated by many higher order modes rather than a single fundamental mode. The advantage of this scheme proposed by Zhang et al [5] is that it can generate very short wakefield pulses on the order of the drive beam pulse length, which is typically at ps level. Therefore the structure may be able to handle much higher gradient than in long pulses. The detailed scheme can be found in ref [5,6]. With four electron bunches of 5 nC each as drive beam, we found that the energy spectrum agrees well with the theory prediction. No witness beam was used in this experiment because witness gun was being refurbished during this experiment. Figure 4 shows the measured energy spectrum of these 4 pulses and the prediction from the theory.

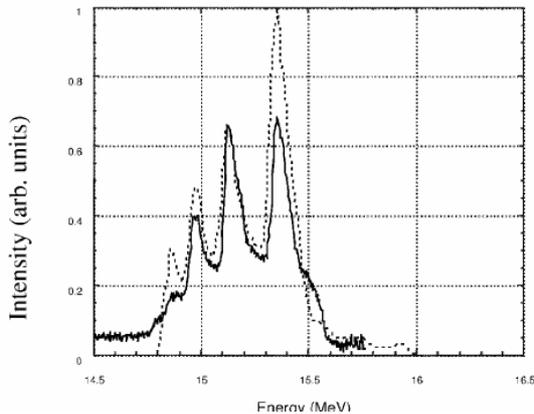


Figure 4: Energy Spectrum of four 4.8 nC bunch train. The solid line is the measured energy spectrum and the dotted line is the theoretical prediction.

### 3 DIELECTRIC BASED TWO BEAM ACCELERATION EXPERIMENT.

An important issue for linear collider development is RF sources. Using bunched train driven dielectric based technology for RF extraction directly has significant advantages since the radiation frequency only depends on the dielectric device geometry. The RF source frequency can be easily tuned to a harmonic of the linac RF frequency with some tuning range (by adjusting the laser spacing for the RF photocathode gun). This RF power is then directly transferred to a second dielectric tube with much higher dielectric constant, compressing the pulse and hence enhancing the acceleration field. This scheme is also called a step-up transformer; the use of separate beam paths allow transformer ratios greater than 2 to be achieved [7]. By using a multiple drive beam, longer acceleration distance can also be achieved, thus obtain higher gradient and sustained accelerations than the collinear schemes. In this section, we report on the proof of principle experimental results on dielectric loaded two beam acceleration experiment. In this experiment, the AWA operates a parallel witness beam line with a magnetic spectrometer for energy measurement of the witness beam. The typical witness beam energy is about 3.9 MeV with charge of 0.5 nC for this experiment. The step-up transformer experiment is shown in Figure 5 schematically.

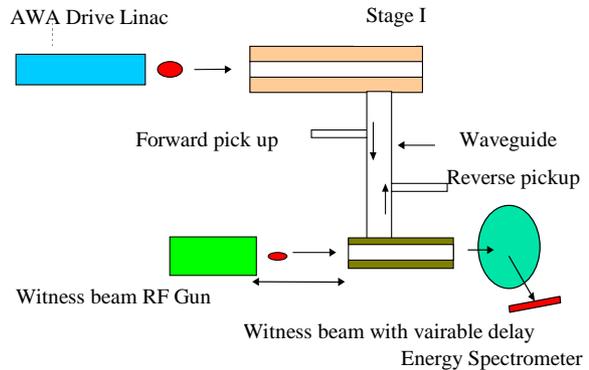


Figure 5: Schematic diagram of the two beam acceleration (step-up transformer) experiment.

The structures used for these experiments were designed to demonstrate the physics of dielectric based two beam acceleration. The choice of operating frequency is 7.8 GHz that is compatible with the drive bunch length available at AWA while also a harmonic of the 1.3 GHz frequency. The device parameters are summarized in Table 1.

The structures were constructed in house and cold tested using a HP8510C network analyzer. It was very challenging to achieve good coupling between the stages because of the wave impedance mismatch between the dielectric loaded waveguide and standard rectangular waveguide. This problem was solved by tapering the dielectric inner radius near the coupling slot so it can act as an impedance transformer. The measured transmission

from stage I to stage II was  $>96\%$ , sufficient for the proof of principle experiment.

TABLE 1: Parameters for staged dielectric step-up transformer

	Stage I	Stage II
Inner Radius a	6 mm	3 mm
Outer radius b	11.15 mm	5.41 mm
Dielectric constant $\epsilon$	4.6	20
Group velocity $\beta_g$	0.25	0.05
$E_z$ (Max)	3 MV/m	8 MV/m
Field step up		2.5
Interaction length for a single beam	30 cm	3 cm

After the structures were constructed, they were installed in the beamline for experiment using electron beam from the drive gun. In this section we discuss the experimental results.

The first experiment conducted was to measure the RF power generated from the stage I dielectric tube. We used a HP spectrum analyzer capable of measurements up to 50 GHz. Figure 6 shows the measured spectrum from the forward power flow. It shows that majority of the energy is concentrated near 7.8 GHz as expected. However, a small peak around 8.3 GHz is not expected and further investigation is needed. Expanding the frequency range showed the second deflection mode at 11 GHz as expected. Due to the finite coupling iris band width, we could not observe the first deflection mode.

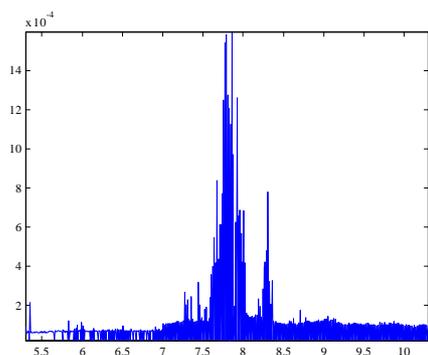


Figure 6: Measured spectrum of the beam induced RF signal from the stage I tube. The energy is concentrated around the  $TM_{01}$  fundamental frequency 7.8 GHz as expected.

The RF power flow was also measured between the two stages. In order to do this, a directional coupler was installed in the transfer waveguide. The forward and reflected RF power signal envelope is detected using a high frequency diode. The measured RF pulse width is 2.5 ns, which agrees very well with the prediction based on the dielectric property and structure length. The timing between the forward and reflected power indicates that the

small reflection is from the coupling iris of the stage II tube. The estimated reflection coefficient is  $<5\%$ , as expected from the bench coupling measurements.

When the witness beam injected into the stage II structure, its energy will change depending on its phase relative to the drive beam. At the AWA, this phase is adjusted by varying simultaneously the laser delay and RF phase to the witness gun [8]. Figure 7 shows the results of a typical measurement. The horizontal axis is the energy (bend) plane of the spectrometer. The top picture is the witness beam imaged on a phosphor screen in the spectrometer focal plane with no drive beam passing through the stage 1 tube. In this experiment, the drive beam charge is  $\sim 20$  nC, which would be expected to generate 1.6 MV/m decelerating gradient in the stage 1 tube (and  $\sim 3$  MV/m peak field) as measured indirectly from the forward RF power (4 MW, in Fig 3). The middle picture shows the witness energy at 56 ps nominal delay. (Note the nominal drive-witness delays given below are measured with respect to an arbitrary zero-delay point). The maximum energy gain is about 250 KeV which is corresponding to about 7.5 MeV/m, agreeing well with the prediction as shown in table 1. Therefore,

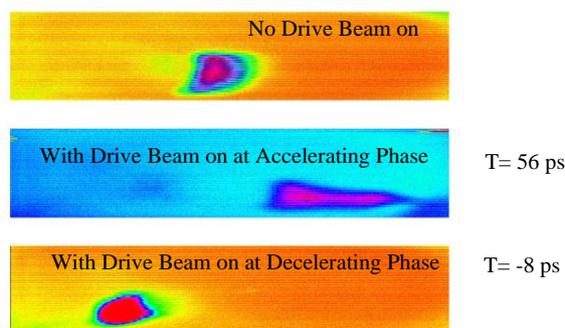


Figure 7: Measured energy change of the witness beam. The top is with drive beam off and middle is with drive beam on and with acceleration phase of beam delay at 56 ps. The bottom shows the deceleration.

the field step-up ratio is  $> 2$  as predicted. Moreover, This also mean the transformer ratio (Maximum accelerating field/maximum decelerating field in driving tube) exceeds 4. This demonstrates experimentally that the wakefield theorem can be violated in a noncollinear geometry devices. When the delay is changed to  $-8$  ps, the witness beam experienced maximum decelerating phase of the wakefields. Thus the wavelength in the second stage is  $\sim 132$  ps, which corresponds to 7.8 GHz excitation in stage II with phase velocity  $c$ .

We have also detailed mapped the acceleration field in stage II by continuously changing the relative delay of drive and witness beam. Figure 8 shows the mapped acceleration field, which is measured centroid witness beam energy change vs delay.

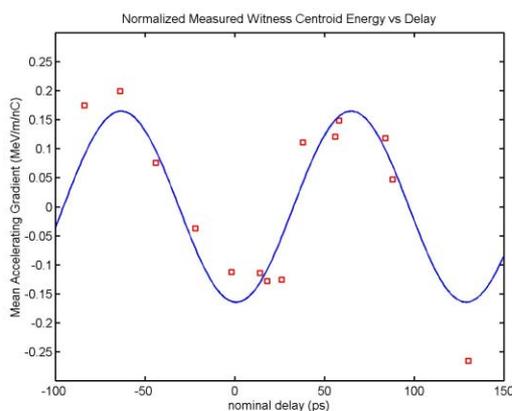


Figure 8: Measured witness beam centroid energy change vs delay.

#### 4 THE CURRENT AWA UPGRADE ACTIVITIES

Although we have successfully tested the step-up transformer concept using the two beam acceleration method, but limiting factors in accessing higher acceleration gradients are the drive beam properties, in particular that the current drive beam has relative high emittance and longer bunch length. A further limiting factor is the number of drive bunches produced due to the quantum efficiency of the photocathode. There is major ongoing effort to improve the drive beam properties by constructing a third generation drive gun [8]. The new gun is a 1- $\frac{1}{2}$  cell RF photocathode gun with axial electric field of 80 –100 MV/m. Based on PARMELA [9] simulations, it will produce much lower emittance (by a factor of 20) and shorter beams (3 – 4ps) for intensities of 40 - 100 nC. Another improvement will come from the operating vacuum and cathode upgrades. We intend to replace the current Mg cathode with a CsTe type high QE cathode.

The gun has been built and installed on the AWA gun test stand. It is conditioned up to 12 MW RF power and reached designed field of more than 80 MV/m on the cathode. Initial test produced photoelectron beam with charge of  $\sim$  20 nC from this new gun. The detailed electron beam properties are underway.

Installation of a new all solid state laser system has completed. The new system consists of a Spectra Physics Tsunami oscillator followed by a Spitfire regenerated amplifier and two multipass Ti:Sapphire amplifiers. With harmonic tripled output, it produces 2 mJ at 248 nm, with a pulse length of 6-8 ps FWHM and a repetition rate of up to 10 pps. The laser has very good power stability ( 2 –

3% rms at UV) and beam profile quality are indeed much better than what the old laser system could provide.

Another improvement will come from the operating vacuum and cathode upgrades. We are in the process to replace the current Mg cathode with a CsTe type high QE cathode. With the expected quantum efficiency of about 1%, we can produce up to 64 pulses with 40 nC each with 1.5 mJ UV. By using the same step up transformer, we would not only achieve 100 MV/m, but also could accelerate the beam to 100 MeV in less than a meter. This is the equivalent of powering the second stage tube with external 500 MW RF power source with a 50 ns pulse length.

#### 5 SUMMARY

Considerable progress has been made towards a demonstration of the dielectric loaded two beam accelerator concept. A proof of principle experiment clarified the associated physics and engineering issues such as RF coupling and acceleration in the correct acceleration mode. With the new AWA electron gun, we will further extend this experiment by using the high current pulse train to provide  $>$  100 MV/m gradient over an acceleration distance of 1 meter. Also this electron beam can be used for studying many advanced acceleration topics such as nonlinear plasma wakefield, high power ( $>$ 100 MW) high frequency ( $>$  30 GHz) RF generation and wakefield excitations of different type structures.

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