Performance of the Argonne Wakefield Accelerator Facility and Initial Experimental Results

W. Gai, M. Conde, G. Cox, R. Konecny, J. Power, P. Schoessow and J. Simpson
High Energy Physics Division, Argonne National Laboratory
Argonne, Illinois 60439, USA

N. Barov
Physics Department, UCLA
Los Angeles, CA 90024, USA

Abstract

The Argonne Wakefield Accelerator (AWA) facility has begun its experimental program. This unique facility is designed to address advanced acceleration research which requires very short, intense electron bunches. The facility incorporates two photo-cathode based electron sources. One produces up to 100 nC, multi-kiloamp 'drive' bunches which are used to excite wakefields in dielectric loaded structures and in plasma. The second source produces much lower intensity 'witness' pulses which are used to probe the fields produced by the drive. The drive and witness pulses can be precisely timed as well as laterally positioned with respect to each other. We discuss commissioning, initial experiments, and outline plans for a proposed 1 GeV demonstration accelerator.

1. Overview of the AWA Facility

The generation of high gradients (> 100 MV/m) in wakefield structures requires a short pulse, high intensity electron drive beam. The main technological challenge of the AWA program is the development of a photo injector capable of fulfilling these requirements. The goal of the AWA is to demonstrate high gradient and sustained acceleration of charged particle beam by using wakefield method. In the past year we have made considerable progress towards attaining the design goals of the AWA.

Fig.1 shows the schematic diagram of the AWA facility, consisting of 3 major components: 1) an L-band rf photocathode and Linac capable of producing a 100 nC electron drive beam; 2) a second L-Band photocathode gun generates a low emittance and low charge beam which probes the wakefield produced by the intense drive beam and 3) An experimental test section for wakefield experiments.

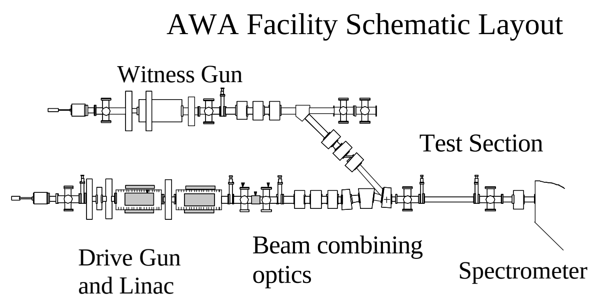

Figure 1. Schematic layout of the AWA facility.

A picosecond UV laser with up to 8 mJ/pulse output is used to illuminate the photocathode for both guns.

In this paper we present detailed descriptions of the facility and initial characterization of its performance. The preliminary results of dielectric and plasma wakefield experiments are discussed. The near and long term plans for experiments and facility upgrades will be described.

2. Photocathode Gun and Drive Linac System

The gun and drive linac are shown in Fig. 2. The laser photocathode sources was designed to deliver 100 nC bunches at 2 MeV to the drive linac. The photocathode gun is a single cell standing wave cavity with designed peak field of 90 MV/m on the cathode [1]. Some of the novel features incorporated into the gun to attain high intensities include a large (2 cm diameter) cathode, the use of a curved laser wave front and nonlinear focusing solenoids matched to the angle-energy correlation computed for the 100 nC bunch. So far, only flat laser pulses have been used for the experiment. However, for most AWA experiments, only 40 ~ 60 nC pulses are needed as discussed below.

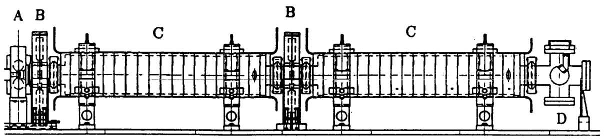

Figure 2. Drive Linac. A: High current photocathdoe gun. B: Focusing Solenoids (bucking solenoid not shown), C: Linac Cavities, D: Laser and diagnostic port.

The AWA drive linac [2] consists of two sections of $\pi/2$ standing wave structures. Each section is about a meter long. The linac is designed to deliver 18 MeV electron beam with 5 ~ 10 % of energy spread at 100 nC.

3. **Witness Gun**

The witness gun a six-cell, copper, iris loaded, rf photocathode operating at 1.3 GHz in a p/2 standing wave mode. A low charge, low emittance witness beam (0.1 nC charge, 1 p mm-mrad 90% physical emittance) is produced to probe (i.e. witness) the wakefields left behind by the drive beam . The witness gun is a scaled down version of the s-band Mark IV accelerator that was used at SLAC, as described in reference [3]. Since the Mark IV Accelerator was a linac, some adjustments were made to turn it into a photocathode gun using the rf design code URMEL. The witness gun has a photocathode in the first 1/2 cell, a coupling iris in the fourth full cell and a beam exit hole in the last half cell.

In order to probe the test devices properly, the witness beam must have a kinetic energy of 4 MeV, a physical emittance of 1 p mm-mrad, an energy spread of less than 1% and a bunch length of about 5 ps. Extensive simulations with PARMELA have shown the Mark IV type gun to be capable of achieving the design parameters. Using a 1.5 mm spot size and a phase launch of 65 degrees we obtain the following results

Energy	90% Emittance	Energy Spread	Bunch Length
4.53 MeV	0.76 p mmmrad	0.5% FW	5.6 psec

4. **Lasers and Control**

The picosecond KrF laser system

The laser consists of a front end that produces picosecond pulses at 248 nm and a final KrF amplifier. The central component of the front end is a synchronously pumped mode locked dye oscillator (Coherent 702). The dye laser is tuned to the desired wavelength of 497 nm by a single-plate birefringence filter. Coumarin 102 dissolved in benzyl alcohol and ethylene glycol is the lasing medium, and DOCI dissolved in benzyl alcohol and ethylene glycol is the saturable absorber. A harmonic tripled mode locked Nd:YAG laser is used to pump the dye laser. The frequency of the mode locker is 40.625 MHz of which the 32nd harmonic is exactly 1.3 GHz.

A single pulse from the dye laser output train is amplified to 300 µJ through a three-stage amplifier. The dye amplifier is Lambda-Physik FL2003 pumped by 100 mJ, 308 nm pulses from a Lambda-Phyisk LPX105i excimer laser. The duration of the pump pulse is shortened to 10 ns so only one pulse from the dye oscillator can be amplified. The output from the dye amplifier is frequency doubled in a 3x3x7mm angle matched BBO crystal. Output at 248 nm is typically 25 - 30 µJ. Because the length of this doubling crystal, temporal broadening of the input pulse is expected.

Amplification of the ultra-short UV pulses is done in a single stage KrF excimer laser (Lambda-Physik LPX105i). The input pulses pass through the amplifier twice in order to fully utilize its stored energy. Typical output of 8 - 10 mJ is obtained routinely. The length of the final pulse is measured by Hamamatsu streak camera (model C1587) which has resolution of 2 ps. The typical measured pulse length (FWHM) is 3 - 4 ps. No satellite pulses observed. Repetition rate of the of the laser can be as high as 35 Hz.

In order to have certain flexibility of the experiment, we can run the Coherent 702 dye laser in a single jet mode. In the single jet mode, the laser is capable of producing pulse length from 5 ps to 30 ps. We have verified the laser pules length by using the autocorrealtor and streak camera. The laser energy is from 5 - 7 mJ/pulse with nominal fluctuation of 10% for the long laser pulses..

Controls and data acquisition

The design of the AWA control system[6] is based in part on the experience gained at the Advanced Accelerator Test facility (AATF), and also on more extensive data acquisition systems used for high energy physics experiments. The goal of the AWA system is to provide easy selection and adjustment of accelerator and beamline parameters, as well as the online analysis of diagnostic and physics data.

At the core of the system is an HP-750 RISC workstation using the UNIX operating system. The workstation is interfaced to VMEbus via a high speed adapter with dual port RAM. A 68060 CPU board on the VMEbus handles command requests from the workstation and provides auxiliary processing capabilities. Most of the control and monitoring functions are handled through a VME-CAMAC parallel bus interface. Video signals from beam position monitors and from the streak camera, comprising the actual physics data from the experiment, are acquired using a high resolution VME-based frame grabber. The AWA control software was developed in house and is based on the Tcl/Tk scripting language. The various codes comprising the system are written in C and FORTRAN77.

5. Initial Characterizations of the drive and witness beam

Detailed characterization of the both AWA drive and witness beam is currently underway. We have made an initial measurement of the beam properties at the exit of the Linac. Attempts were made to measure the pulse length and emittance vs the charge.

One unexpected problem encountered during the experiment was the low observed quantum efficiency of Magnesium photocathode, compared to measurements reported in the literature [4]. The QE found for Mg is 1~ 1.5×10^{-4}. Hence almost all the available laser energy is required to generate a 100 nC beam. However, a higher intensity laser pulse generally induces the photocathode to emit electron continuously ("explosive mode") [5]. Therefore, our initial measurements were made with charges generally less than 100 nC.

A diagnostic port at the exit of the Linac consists of an insertable pepper pot and a phosphor screen for emittance measurements. A calibrated integrated current transformer (ICT) device is used here for online nondestructive charge monitoring and a thin quartz (1 mm thick) plate is used as a Cherenkov radiator for pulse length measurement.

High Charge Generation

A 20-27 nC beam can be produced by 1 mJ laser pulse regardless the laser pulse length. It appears that we run into the space charge limit when we increase the laser power to 2 - 3mJ for short laser (5 ps). The maximum charge produced is 55 nC with 5 mJ of laser power. Increasing the laser pulse length resulted in higher charges as expected. A 100nC per pulse were observed, and 90nC pulses can be reached consistently with 5mJ laser power

Pulse Length Measurement

The electron pulse length is measured by using a streak camera situated in the laser room. The Cherenkov light from the quartz plate in the diagnostic port is collected and transported to the laser room. The Cherenkov light transport line was carefully built to ensure that no electron beam information can be lost.

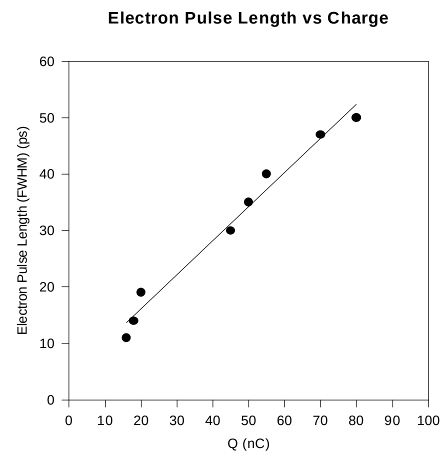

Fig 3 Electron pulse length vs charge

Results of the measurement are summarized in Figure 4. Because the electron pulse is not a gaussian, all the data were characterized by the full width half maximum (FWHM). The bunch length has a strong dependence on the charge. The shortest bunch length is 11 ps for 18 nC beam. At each charge, we average several data points to minimize the "random error" due to the pulse to pelse charge fluctuations. For 80 nC beam (with long laser pulse length), the measured electron pulse length is 48 ps, longer than the design goal (100 nC, 30ps). We are in the process of setting up an experiment for further investigation to attempt to reduce the bunch length. Note that while the Linac focusing is optimized for the curved laser bunch, only planar wavefront laser beam have been used

Emittance Measurement

A "pepper pot" with 0.5 mm holes and 2.5 mm spacing with a phosphor plate placed 40 cm downstream used for emittance measurement. Because of the small electron beam spot and relatively large holes of the pepper pot, and the resolution is about 10 mm mrad. Therefore, we have only estimated an upper limit on the emittance.

The following table summarizes the results of several measurements.

Charge	Measured rms physical emittance
20nC	10 mm mrad
55nC	13 mm mrad
70nC	20 mm mrad

The Witness Beam

The witness gun and its associated beam lines were recently installed and commissioned. Properties of the witness beam are being studied. The charge produced in the witness gun ranges from 0.1 ~ 3 nC. The beam energy is 4 MeV. The beam has been used for the initial dielectric wakefield measurements. Emittance measurements using a quadrupole scan technique and bunch length measurements using Cherenkov radiation are underway.

Synchronization of the drive and witness beam

Once the drive beam and the witness beam are generated, both beams are transported to the experimental section and combined. Since both the drive and witness beam are generated using the same laser pulse, a laser beam splitter is used to reflect a small amount of the laser beam through an adjustable delayed. Time delay between the two beams can be adjusted precisely using a mirror mounted on a movable stage for the witness laser beam line, while at the sametime, adjusting the rf phase to the witness gun to maintain a constant laser injection phase. The typical delay range used in the wakefield experiments is -50 ps to 400 ps. Delays up to 10 ns are possible using this system limited only by the adjustable stage.

6. **Initial Wakefield Experiment Results**

We have performed several collinear wakefield experiments to verify the performance of the AWA facility. Initial choice of the wakefield device were dielectric structure fabricated from Borosilicate glass. This material has a sufficiently large DC conductivity to minimize charging effects during beam tuning when scraping of the drive beam is worst.

Dielectric Wakefield Experiment

We have measured the wake field in two different dielectric structures (7 and 15 GHz). The results for the 7 GHz structure are shown in Figure 4. The wake amplitude is 1.5 MV/m for 20 nC drive beam. The structure has an inner radius of 1.25 cm and an outer radius of 1.6 cm with dielectric constant of 4. The measured wakefield amplitude and frequencies agree well the theory. This directly tested all the components of the AWA facility, and the results are satisfactory.

Another dielectric tube with inner radius 5 mm and outer radius 7.7 mm was also studied in the wakefield experiments. The resonant frequency for this tube is 15 GHz. A wakefield amplitude of > 5 MV/m was observed. Further tuning of the drive beam (more charge and shorter pulse length) should produce a wakefield in the excess of 15 MV/m in this structure.

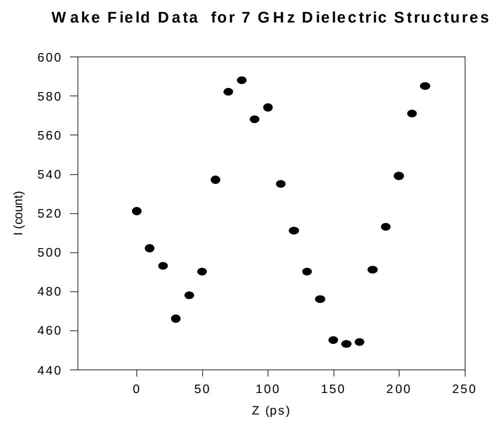

Figure 4. Measured longitudinal wakefield for the 7 GHz dielectric wakefield structure. The peak corresponds to 1.5 MV/m.

Plasma Wakefield Acceleration and Focusing Experiment

In collaboration with an UCLA group, we have performed several preliminary experiments to study the plasma wakefield acceleration in the blowout regime. The first set of experiments demonstrated acceleration of a witness beam as a result of the plasma wave excitation caused by the drive beam. There is a current effort to study the self focusing of the drive beam. In order for the drive beam energy to be optimally coupled to the plasma wave, the drive beam must be focused to a very small spot, and the radius of a significant part of the beam must be kept nearly constant by the plasma's focusing force for the length of the plasma. The aim of the current experiment is to quantify this focusing and propagation, which depends greatly on the beam's emittance, charge and initial matching, as well as on the plasma properties.

7. **Future Planned Experiment**

Near term plans

a). Fully characterize the AWA beams, particularly the drive beam. Studying the beam properties (bunch length and emittance vs charge) dependence on the machine parameters.
b). High gradient collinear wakefield experiments using a dielectric structures. Generation of a electron pulse train and test the step-up transformer concepts. Ultimately to test the dielectric breakdown of the dielectric materials.
c). Continuation of nonlinear plasma focusing and acceleration experiments.
d). Colinear Wakefield Plasma Experiment. This experiment will be very similar to the AATF experiment [6]. Since the drive beam charge from the AWA is much higher than the charge from AATF, one should expect much more intense wakefield. Although this experiment will be in the non-blowout regime, we still believe it is very interesting. We can scan the charge from 2 nC ~ 40 nC in the range of plasma densities of $10^{12} \sim 5x10^{13}$. The justification of this experiment is that although PWFA has been a subject of the intense theoretical investigations, no one has experimentally studied PWFA in detail. Since we have the capability of mapping out the wakefields, this experiment should be straightforward to carry out. The expected acceleration gradient produced in the plasma would be in the range of 10 - 50 MV/m.

Long term plan

Its well know that a major constraint of collinear wakefield acceleration is the transformer ratio. To overcome this difficulty, an accelerating field step-up transformer scheme of the dielectric wakefield accelerator was proposed[7]. The approach is to extract rf power from an intense drive beam traveling in a relatively large diameter dielectric wake field tube (stage I). This power is then transferred to a smaller diameter dielectric loaded guide (stage II) where the enhanced axial electric field is used to accelerate electrons. Field enhancement results both from a lower group velocity in stage II than in stage I (longitudinal compression), and from geometrical effects made possible by the use of the dielectric loaded guide (transverse compression). High net acceleration can be realized if one uses a train of large number (10 - 20) electron pulses. The spacing of the drive pulses can be arranged in such way that a long rf pulse is generated to fill stage II. This also permits us to identify less stringent parameters for the drive beam than previously described. Using this new procedure we predict that Phase-I of the AWA (20 MeV drive beam) can accelerate a witness beam to over 100 MeV in a meter or less.

The current plans for the AWA (phase I) is to generate 40 nC, 20 ps long electron pulse train consisting of 10 -20 pulses. Further upgrade of the drive beam energy in excess of 100 MeV (phase II) without changing any of other parameters would enable us to achieve net acceleration of the witness beam to 1 GeV energy in a less of 10 meters. Therefore, successful demonstration of the multiple pulse driven step-up transformer is critical.

8. **Summary**

Installation of the AWA Phase I facility has been completed. The facility was successfully commissioned. The drive gun and Linac has produced up to 100 nC beam with maximum pulse length of 50 ps (FWHM). The witness gun has produced high quality beams being used for the wakefield experiments. More detailed characterizations of both beams are currently underway. Initial collinear dielectric wakefield experiments verified the new wakefield measurement system. High gradient wakefield acceleration experiments in dielectric structures and in plasma are being pursued.

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