

# Measurements of the Argonne Wakefield Accelerator's Low Charge, 4 MeV RF Photocathode Witness Beam

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## ABSTRACT

The Argonne Wakefield Accelerator's (AWA) witness RF photocathode gun produced its first electron beam in April of 1996. We have characterized the charge, energy, emittance and bunch length of the witness beam over the last several months. The emittance was measured by both a quad scan that fitted for space charge using an in house developed Mathematica routine and a pepper pot technique. The bunch length was measured by imaging Cherenkov light from a quartz plate to a Hamamatsu streak camera with 2 psec resolution. A beam energy of 3.9 MeV was measured with a 6 inch round pole spectrometer while a beam charge was measured with both an ICT and a Faraday Cup. Although the gun will normally be run at 100 pC it has produced charges from 10 pC to 4 nC. All results of the measurements to date are presented here.

## I. INTRODUCTION

The central purpose of the AWA [Schoessow, 95] is to study high gradient acceleration schemes in dielectric structures [Rosing, 90] and in plasmas [Barov, 95]. An extremely high charge (100 nC) and relatively short electron bunch (FWHM less than 50 ps) is necessary to produce gradients that surpass today's conventional gradients. This high charge bunch is called the drive beam [Ho, 92]. Once the high gradient electromagnetic wave is excited in the structure, a low charge (100 pC) electron bunch is injected into the structure to witness the fields. This low charge bunch is called the witness beam [Power, 95].

In this paper the results of the characterization of the witness beam are presented. The characterization done here includes measurements of charge, energy, bunch length, and emittance.

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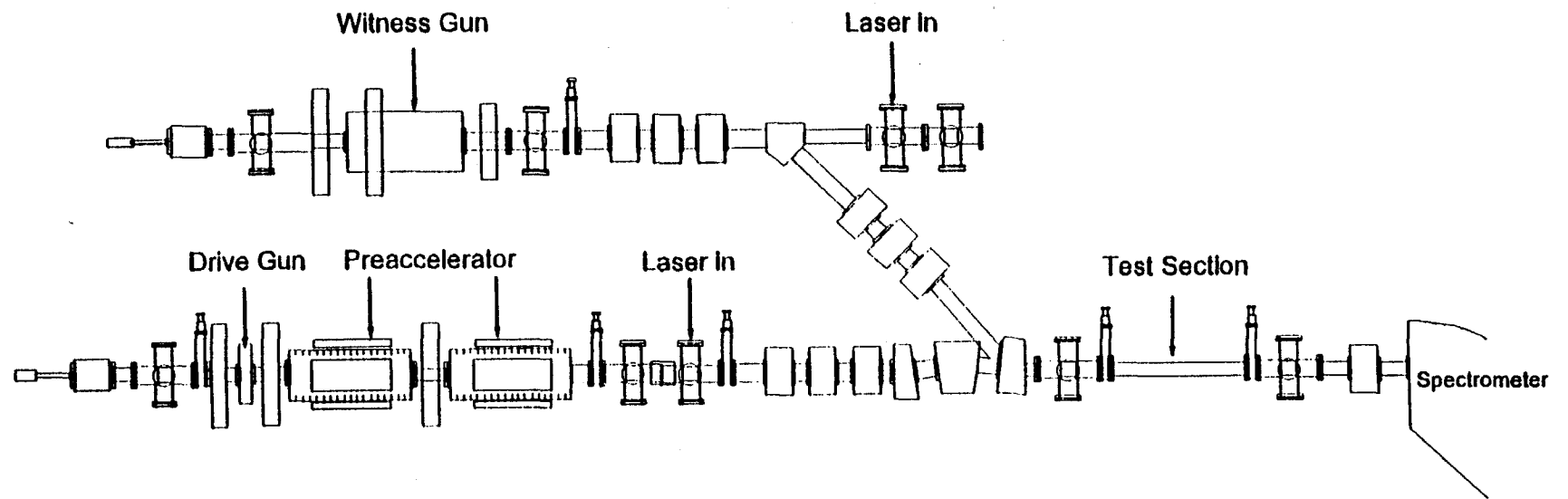
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**Figure 1. Plan View of the Drive and Witness Beam Lines**

## II. AWA FACILITY

The AWA employs two RF photocathode guns to create the drive and witness beams. A schematic diagram of the AWA facility is given in Figure 1 showing the drive and witness beam photocathode gun. A complete facility discussion can be found in the reference [Schoessow, 95].

The drive and witness beams are individually steered and focused into the test section (Figure 1) where either a dielectric tube or plasma cell resides. The laser pulse enters the vacuum system through a UV quality quartz window and is reflected toward the PC gun by internally mounted UV mirrors situated off-axis. The drive beam exits the gun at an energy of about 2 MeV and is immediately injected into the drive linac preaccelerator [Chojnacki, 93] where it is further accelerated to 16 MeV. A 4 MeV beam is ejected out of the witness gun into an achromatic and isochronous transport line. The two beams are combined by a bending magnet from which they emerge collinearly for propagation into the test section. Finally, the drive beam is directed into a beam dump and the energy of the witness beam is resolved in a spectrometer immediately following the test section.

## III. BEAM GOALS

Witness beam parameters were chosen by considering what type of beam would make the best probe for wakefield measurements. A complete beam parameter set, which includes the charge, energy, emittance, bunch length, and energy spread of the witness beam is briefly discussed here. A more thorough discussion of this procedure is given in the reference [Power, 96].

The witness beam energy of 4 MeV was chosen for two reasons. First, an energy near 4 MeV is easy to resolve in the spectrometer since it is well separated from the 16 MeV drive beam. Second, the beam has  $\beta = .994$  which has relatively little phase slippage compared to the drive beam's  $\beta = .9995$ .

In general, a good probe should not significantly change the parameter being measured, while still being easy to observe. A charge of 100 pC is sufficiently low so as not to significantly perturb the wakefield being measured while still being easy to observe on the phosphor screen beyond the spectrometer.

The emittance need only be small enough to allow the beam to transport from the gun to the test section with most of the charge out of the gun. The other consideration is that the beam transport through the same test section that the drive beam passes through. Since the drive beam has a normalized rms emittance of 400 mm mrad there is very little need to keep the beam emittance low. An emittance on the order of 1 mm mrad is more than adequate.

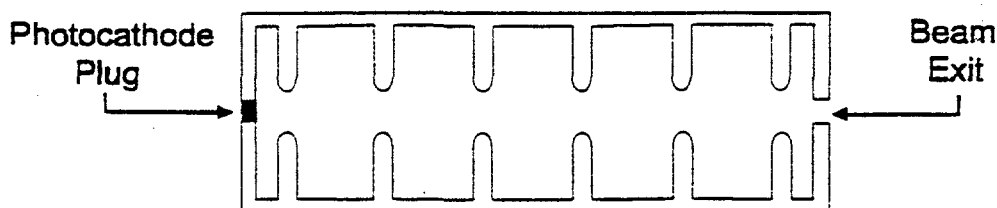
We would like the bunch length of the test charge to be much less than the wavelength of the excited wakefield. At the speed of light a 1.0 mm bunch

spans 3.3 ps of the RF wave which for a 10 GHz wave is 12 degrees of its RF cycle. This is about the shortest bunch that can be easily produced from our RF photocathode gun at 100 pC, and we must target for this number. The reason we are able to tolerate this long bunch (12°) is that we are interested primarily in measuring the peak gradient of the RF wave which can be measured by studying the witness beam centroid.

Wakefield measurements are taken by measuring a change in energy of the witness beam as described in Chapter 7. At first thought, this would seem to imply that the resolution of the wakefield measurement is determined by the energy spread of the witness bunch. However, this is not strictly true since the wakefield measurement depends on the beam energy centroid, which can be determined much more accurately than the full energy distribution of the bunch. Thus energy spread is not a primary limitation. Under 1% rms is adequate.

#### IV. GUN DESIGN

The AWA witness gun chosen was a six cell,  $\pi/2$  mode, iris-loaded, RF photocathode gun. The gun can be described as a copper cylinder with six copper washers placed inside along its axis. Figure 2 is a side view of the cavity showing the five full cells surrounded by the two half cells. In the left most half-cell (the upstream half-cell) is an extractable photocathode plug where the laser strikes to produce photoelectrons. In the right-most half cell (the downstream half cell) is the hole that allows the laser beam to enter and electrons to exit.



**Figure 2.** The Witness Gun for the AWA. A Side View of the Entire Gun. The Plug at the Beginning and the Exit Hole at the End of the Cavity.

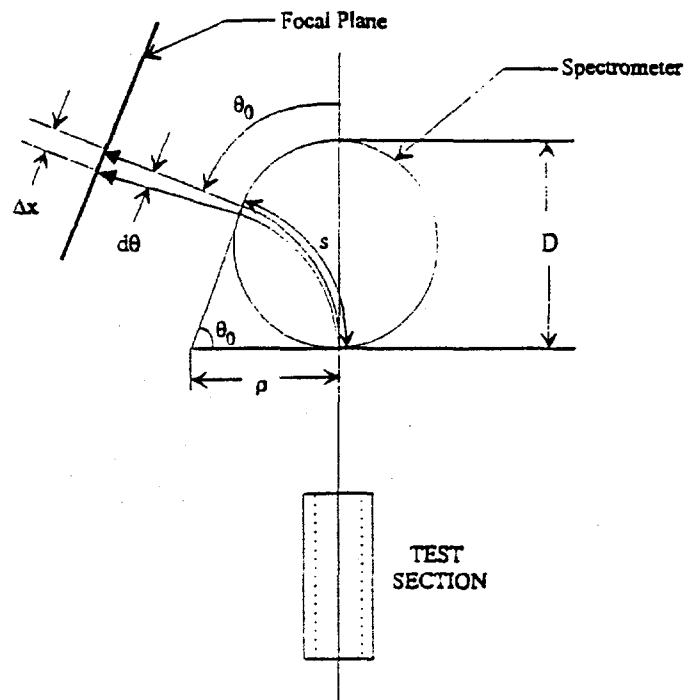
PARMELA simulations showed [Power, 95] that this  $\pi/2$  gun meets the design requirements outlined above. For 3.8 MW of RF power the witness gun produces a 4 MeV, 100 pC beam with a FW energy spread of 0.75% and an emittance of 1.9 mm mrad.

#### V. MEASUREMENTS

The charge is measured immediately after the witness gun (see Figure 1) with an integrating current transformer (ICT) from Bergoz. The ICT is an on-line, non-destructive current monitor that integrates the total charge passing

through its center, with a rise time of about 10 ns. Since we are operating at 30 Hz, we can use the ICT as a single shot charge monitor with a fast digitizing scope to integrate the area under the voltage curve. The ICT was calibrated with a Wavetek function generator and was found to produce a peak output voltage signal of 72 mV/nC. The witness beam charge has been measured over a range of 10 pC to 4 nC.

The energy and energy spread measurements were made with a magnetic spectrometer at the end of the beam line as shown in Figure 3. The spectrometer is a  $D = 6$  inch diameter, round-dipole magnet and vacuum chamber with ports located at the  $\theta_0 = 60^\circ$  and  $\theta_0 = 0^\circ$  (the undeflected position). Energy



**Figure 3.** The Energy Spectrometer Following the Test Section Used to Measure Energy and Energy Spread

measurements are taken by bending the beam through an angle,  $\theta_0$ , with a known magnetic field,  $B$ , and calculating the momentum according to

$$\theta(\text{deg}) = 1.71 \left( \frac{BL[G \cdot m]}{p[MeV/c]} \right) \quad (1)$$

where  $B$  is the magnetic field strength,  $p$  is the momentum, and  $L$  is the effective length of the dipole. (An effective length must be used here since the magnetic field does not drop to zero at the pole edge.) The effective length for the  $\theta_0 = 60^\circ$  port is 17.0 cm. The witness beam was centered on the  $60^\circ$  port for a mag-

netic field,  $B = 895$  Gauss; corresponding to a momentum,  $p = 3.81$  MeV/c and a kinetic energy,  $T = 3.85$  MeV.

The energy spread is best measured in a region of high dispersion. In the case of the witness beam a spot size measurement is made on the focal plane shown in Figure 3 where the beam width is indicated by  $\Delta x$  in the figure. The dispersion function,  $D$ , and its derivative,  $D'$ , increase in a dipole according to [Wiedemann, 93]

$$D(s) = \rho_0 \left( 1 - \cos \frac{s}{\rho_0} \right) \quad (2)$$

$$D'(s) = \sin \frac{s}{\rho_0} \quad (3)$$

where  $s$  is the path length and  $\rho_0$  is the bending radius. Outside the dipole, the dispersion grows according to the formula

$$D(s) = D(s=0) + D'(s=0)\Delta s \quad (4)$$

The bending radius of the dipole at the 60° port is calculated to be  $\rho = 13.1$  cm and the distance from the pole edge to the focal plane is 120 cm. Using Equations 2-4 we find the dispersion to be 60 cm at the focal plane.

In the case of the energy spread measurement for the witness beam we can only give a highly overestimated upper limit. This is because we have violated the requirement that the betatron term is negligible compared to the dispersion term. The betatron function is normally made small at the focal plane by placing a horizontally focusing quad directly in front of the spectrometer and then focusing the beam to a minimum (i.e. small  $\beta_x$ ), so that the width that remains is due to the energy spread, not the emittance. At the time the measurements were taken, there was no quad in front of the spectrometer. In our case we measured a spot size of  $\Delta x = 1.0$  cm which gives an upper limit to the energy spread,  $\delta < 1.6\%$ .

The emittance was measured by a quad scan technique with a screen in a diagnostic chamber beyond the bend magnet at the top of Figure 1 and by varying the first quad after the witness gun in Figure 1. A new quad scan technique [Power, 96b] is used that includes space charge.

The envelope of a round beam,  $r = R$  (the maximum  $r$  value of a particle in the bunch) is a surface that surrounds all the particles in the beam in the transverse direction. The beam envelope [Reiser, 94] evolves along the  $s$  axis according to

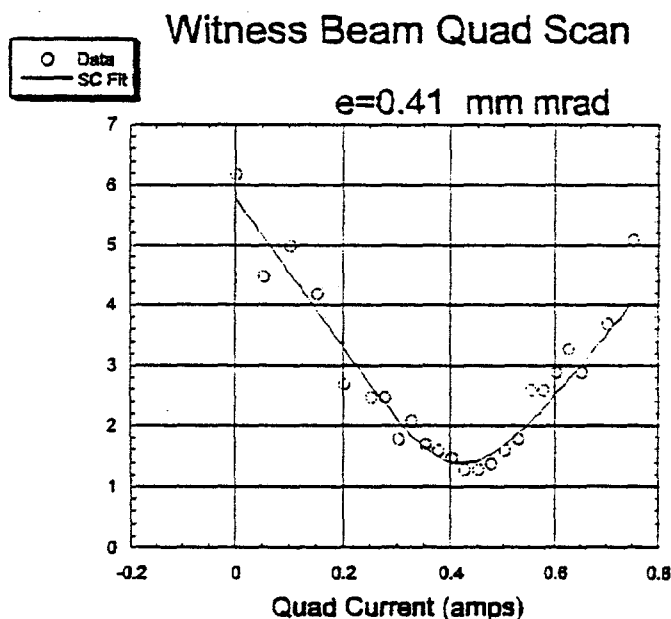


$$R''(s) = \frac{\varepsilon^2}{R^3(s)} + \frac{K}{R(s)} \quad (5)$$

where the derivative is taken with respect to  $s$ , and  $K$  is the perveance [Lawson, 88] in vacuum

$$K = \frac{I}{I_0} \frac{2}{\beta^3 \gamma^3} \quad (6)$$

where  $I$  is the beam current and  $I_0$  is the Alfven current equal to 17 kA. As opposed to most quad scans, we keep the space charge term in Equation 5 for our fit of the data. The resulting fit involves a non-linear least squares fit and is done with a Mathematica routine written by this author. The normalized emittance measured by this new quad scan technique is 3.4 mm mrad. The geometrical emittance is  $3.4/\beta\gamma = 0.41$  mm mrad as shown in Figure 4 (where  $\beta\gamma$  is equal to 8.6).



**Figure 4.** Quad Scan for the Witness Beam

The bunch length is measured by sending the witness beam through a piece of quartz plate and imaging the subsequent Cherenkov light into a Hamamatsu streak camera.

The light from the quartz plate is imaged onto the entrance slit of the streak camera set to a slit width 25  $\mu\text{m}$ . Using the fastest sweep rate on the streak camera we have a measured resolution of 3 ps.

A streak camera measurement of the witness beam is shown in Figure 5. For this measurement, the FWHM bunch length is 10 ps.

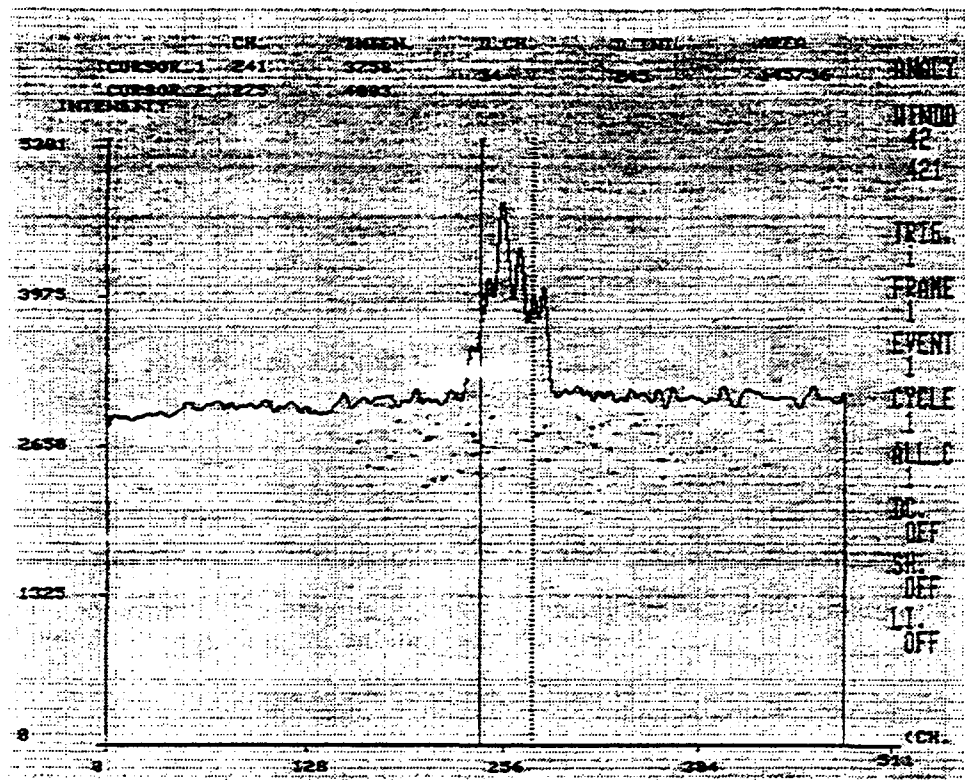


Figure 5. Streak Camera Image of the Witness Beam.  $\Delta Z = 10$  ps FWHM

## VI. CONCLUSIONS

The end result of this work is a functioning, wakefield measurement system. This system has been used to measure the first wakefields produced at the AWA with these early measurements at 7 MV/m. The wakefield measurement system consists of a 6 cell,  $\pi/2$ , RF photocathode gun, transport lines to deliver both the drive and witness beams to the test section, and a synchronization system responsible for the timing between the drive and witness beams.

The RF photocathode gun used to generate the witness beam has produced an electron beam with an energy of 4 MeV, a charge of 100 pC, a normalized transverse emittance of  $3.4 \pi$  mm mrad, and a FWHM bunch length of 10 ps. The beam was characterized using a spectrometer for energy, an integrating current transformer for charge, a new quad scan technique for emittance, and a streak camera for bunch length. The beam characterization is found to agree well with the predictions of the PARMELA simulations.

## VI. ACKNOWLEDGMENTS

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