

# A COMPACT WAKEFIELD MEASUREMENT FACILITY\*

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## Abstract

The conceptual design of a compact, photoinjector-based, facility for high precision measurements of wakefields is presented. This work is motivated by the need for a thorough understanding of beam induced wakefield effects for any future linear collider. We propose to use a high brightness photoinjector to generate (approximately) a 2 nC, 2 mm-mrad drive beam at 20 MeV to excite wakefields and a second photoinjector to generate a 5 MeV, variably delayed, trailing witness beam to probe both the longitudinal and transverse wakefields in the structure under test. Initial estimates show that we can detect a minimum measurable dipole transverse wake function of 0.1 V/pC/m/mm and a minimum measurable monopole longitudinal wake function of 2.5 V/pC/m. Simulations results for the high brightness photoinjector, calculations of the facility's wakefield measurement resolution, and the facility layout are presented.

## INTRODUCTION

A fundamental concern for the NLC is the beam-induced wakefield effect. In general, the short-range wake acts back on the beam and degrades its quality, while the long-range wake deleteriously affects subsequent bunches. Wakefield effects, such as those due to RMS structure misalignment and schemes to suppress these effects (e.g. emittance bumps), have been studied mainly with numerical calculations and with previous machines, such as the SLC. These techniques, however, will work at the NLC only if the structure wakefields are below certain thresholds. For example, the RMS structure misalignment must be less than 20  $\mu\text{m}$  to avoid resonant instabilities. For quality control reasons, it would be beneficial if the wakefield characteristics of the NLC structures were accurately measured before being installed into NLC accelerating modules. We propose to characterize these structures by directly mapping their wakefields [1].

Direct mapping of the wake function of NLC structures was previously made at the AATF [2], with moderate precision using approximately 10 MeV beams, and also at ASSET [3], with high precision using approximately 1 GeV beams. In this paper, we present a zero<sup>th</sup> order design study that shows that direct-wakefield measurements can be made with high precision using 10 MeV beams if the facility is based on high-brightness RF photocathode guns [4]. Such a facility could then be used as the basis of an NLC quality control center.

## FACILITY OVERVIEW

A compact, collinear, direct-wakefield measurement facility [Fig. 1] can be made using a high-brightness, 20

MeV, 2 nC drive beam to excite the wakefields and a high-brightness, 5 MeV, 0.1 nC witness beam to probe the wakefields. For wakefield measurements, a beamline is designed to transport the drive and witness beams collinearly through the structure. The longitudinal location of the witness beam with respect to the drive beam can be continuously varied from a time delay  $t$  of one nanosecond ahead of the drive to tens of nanoseconds behind it. This is accomplished by varying the optical delay path of the laser pulse generating the witness beam in conjunction with an adjustment to the phase of the RF into the witness gun.

The drive beam is matched from the output of the drive gun and linac (not shown) to the drive beam lattice (quad (Q) triplet and dipole (D) chicane) and through the NLC structure. In a similar fashion, the witness beam is delivered through a dog-leg section and into the NLC structure. Initial alignment of the drive (witness) beam through the structure is done while blocking the witness (drive) beam and centering the drive (witness) beam on the *straight-through zeroing BPM*.

## Measurement of the Longitudinal Wake

Upon exiting the structure, the drive and witness beams are separated by a horizontal dipole magnet ( $H$ ) that bends the beams by approximately  $2.5^\circ$  and  $10^\circ$  respectively. With the witness beam running in front of the drive beam, the horizontal dipole magnet,  $H$ , is adjusted until the witness beam is centered in the horizontal direction on the *witness-beam zeroing BPM (WB-ZBPM)*. To measure the monopole longitudinal wake function the structure is centered (zero offset with respect to the beams) and the witness beam is positioned at a time  $t$  behind the drive beam. The longitudinal wakefield is proportional to the longitudinal momentum kick received by the witness beam,

$$\Delta\theta_z(t) = \frac{\gamma}{\gamma+1} \left( \frac{\Delta E_z(t)}{E} \right) \quad (1)$$

where  $\gamma$  is the relativistic energy factor,  $E$  is the energy of the witness beam (5 MeV), and  $\Delta E_z$  is the longitudinal energy change of the witness beam centroid. After exiting  $H$ , the drive beam is dumped and the witness beam is directed towards a weak vertical dipole magnet ( $V$ ) and the *WB-ZBPM*. Conceptually, one could simply measure the horizontal offset at *WB-ZBPM* to infer the energy change ( $\Delta E_z$ ) of the witness beam centroid. However, from the point of view of beam optics and BPM resolution, it is better to use  $H$  to center the witness beam centroid on *WB-ZBPM* and then use this change to the magnetic field of  $H$  to calculate the change in energy,  $\Delta E_z$ .

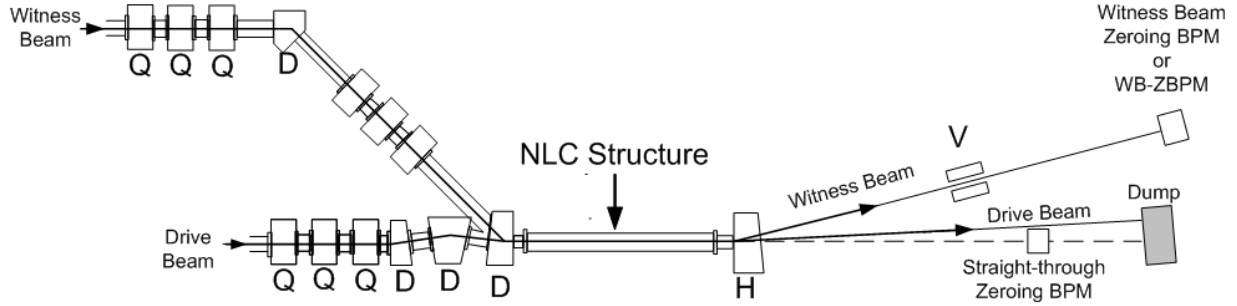


Figure 1: Block Diagram of the Compact Wakefield Measurement Facility.

### Measurement of the Transverse Wake

To measure the dipole transverse wake function the structure is displaced 1 mm in the vertical direction relative to the collinear drive and witness beams. The witness beam is then placed at time  $t$  behind the drive bunch, which causes the trailing witness beam to receive a vertical deflection,

$$\Delta\theta_y = \frac{\gamma}{\gamma+1} \left( \frac{\Delta E_y}{E} \right) \quad (2)$$

where  $\Delta E_y$  is the transverse energy change of the witness beam centroid. To compensate for the longitudinal wake, the magnet  $H$  is again used to horizontally center the witness beam on WB-ZBPM. The vertical deflection of the witness beam ( $\Delta\theta_y$ ) will cause the beam to be displaced in the vertical direction (out of the plane in Figure 1) at WB-ZBPM. Once again, conceptually, we could measure this vertical offset, at WB-ZBPM, to infer the strength of the transverse wake, but for practical purposes it is better to use the vertical dipole magnet  $V$ , to center the witness beam on WB-ZBPM and use the change in magnetic field strength of  $V$  to infer  $\Delta\theta_y$ .

### Machine Functions

The machine functions for matching the drive and witness beams through the structure and into the measurement area were found with COMFORT [5]. The results are shown in Figure 2 and Figure 3.

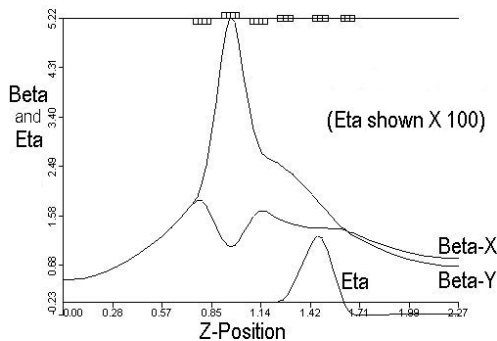


Figure 2: Drive beam machine functions from the end of the drive linac to the center of the NLC structure.

## HIGH BRIGHTNESS ELECTRON SOURCE

A new 1 1/2 Cell L-band (1.3 GHz) RF photocathode gun at the Argonne Wakefield Accelerator (AWA) facility has recently been commissioned. The primary purpose of this gun is to generate high-intensity beams, with a nominal bunch charge of 100 nC, for studying wakefield acceleration schemes. The beam produced by the gun in this *high-intensity mode* is not suitable for characterization of NLC structures due to the large normalized beam emittance of approximately 100 mm-mrad.

In order to determine if this gun can be operated in a *high-brightness mode* to generate the drive beam, we first spend a moment to discuss the requirements of the drive beam. The maximum allowable emittance of the electron source is estimated by examining the dimensions of an NLC structure and then requiring that the beam be able to pass through it. Typical NLC structures currently under consideration are about 1 meter long with an inner radius of the iris near 3 mm. We choose a comfortable safety margin by requiring that the beam's one-sigma radius be about an order of magnitude less than the iris radius, or  $\sigma_{x,y} \approx 300 \mu\text{m}$ . Assuming that: (1) the beam is focused to a waist at the center of the structure; (2) the beta function is one meter, or  $\beta = 1 \text{ m}$ ; and (3) the normalized energy of the beam is  $\gamma = 40$ ; then the maximum allowable normalized emittance from  $\sqrt{\epsilon\beta} = 300 \mu\text{m}$  is  $\epsilon_n^{\text{max}} = 3.6 \text{ mm mrad}$ .

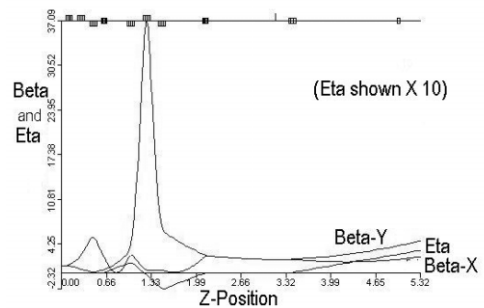


Figure 3: Witness beam machine functions from the end of the witness gun to WB-ZBPM.

Table 1: High-Brightness Gun Operating Mode

<b>Charge (nC)</b>	2
<b>Laser spot radius (mm)</b>	1.6
<b>Laser pulse length (psec)</b>	8
<b>RF launch phase (<math>^\circ</math>)</b>	40
<b>Energy (MeV)</b>	10.4
<b>Energy spread (%)</b>	0.5%
<b>Normalized r.m.s. emittance (mm mrad)</b>	1.9

Our second requirement is to operate the drive gun at the highest possible charge to increase our wake function measurement sensitivity. Recent Parmela [6] simulations indicate that the gun can indeed be operated in a *high-brightness mode*. The beam parameters produced by the AWA gun operating in high-brightness mode are summarized in Table 1. It is worth pointing out that this operating point uses a drive beam charge of 2 nC that easily satisfies the drive beam requirements.

## RESOLUTION OF THE WAKEFIELD MEASUREMENT SYSTEM

In this section we put all the previous sections together and make an estimate of our measurement resolution.

### Longitudinal Wakefield Resolution

The longitudinal momentum kick (see Eq. 1) is related to the longitudinal wake function by,

$$\Delta\theta_z(t) = \frac{\gamma}{\gamma+1} \left( \frac{-eQ_d L_s W'_{\parallel,0}(t)}{E} \right) \quad (3)$$

where  $Q_d$  is the drive bunch charge in pC,  $L_s$  is the structure length in meters,  $E$  is the witness beam energy in units of eV,  $W'_{\parallel,0}(t)$  is the monopole ( $m=0$ ) longitudinal wake function [7] per unit length in units of V/pC/m, and the prime stands for differentiation in the  $z$  direction. From this equation we can see that we will achieve good sensitivity to the wake function (i.e. a large kick) if  $Q_d$  is large and  $E$  is small. Since  $Q_d$  and  $E$  are fixed at 2 nC and 5 MeV, respectively, then the resolution depends on the accuracy to which we can measure the energy change,  $\Delta E_z/E$ .

If the witness beam charge is 10 pC, we can estimate a normalized r.m.s. emittance of 0.1 mm mrad and a momentum spread of 1%. From figure 3, we see that the horizontal beta function of the witness beam is  $\beta_x = 2.6$  m and the dispersion is  $\eta_x = 0.2$  m at WB-ZBPM. The width due to the beta function ( $\sigma_\beta = 0.5$  mm) is added in quadrature with the width due to the momentum spread and dispersion function ( $\sigma_\eta = 2.0$  mm) to give the total width ( $\sigma_{\text{tot}} = 2.1$  mm). We now assume that the accuracy of WB-ZBPM is about  $1/10^{\text{th}}$  of the one sigma beam width, or 210  $\mu\text{m}$ . Since  $H$  bends the witness beam by  $10^\circ$ , then a 0.1% change in longitudinal momentum over a 2 m drift will produce a horizontal offset of the witness beam centroid at WB-ZBPM of 350  $\mu\text{m}$ , comfortably

larger than the resolution of WB-ZBPM. Finally, combining equations 1 and 3, and solving for  $W'_{\parallel,0}(t)$  gives a minimum measurable monopole longitudinal wake function per unit length of 2.5 V/pC/m.

### Transverse Wakefield Resolution

The transverse momentum kick (see Eq. 1) is related to the transverse wake function by,

$$\Delta\theta_y(t) = \frac{\gamma}{\gamma+1} \left( \frac{-eQ_d L_s W'_{\perp,1}(t)}{E} \right) \Delta y_d \quad (4)$$

where  $W'_{\perp,1}(t)$  is the dipole ( $m=1$ ) transverse wake function per unit length in units of V/pC/m/mm,  $\Delta y_d$  is the offset of the drive beam relative to the center of the structure measured in mm, and all other variables have been previously defined.. Once again, good sensitivity to the transverse wake function is obtained when  $Q_d$  is large and  $E$  is small.

From figure 3, we see that the vertical beta function of the witness beam is  $\beta_y = 4.6$  m leading to a vertical beam size of  $\sigma_\beta = 0.4$  mm at WB-ZBPM. Once again, we assume that our BPM resolution is  $1/10^{\text{th}}$  of the spot size, so that the vertical BPM resolution is 40  $\mu\text{m}$ . Next, we estimate the minimum angular kick ( $\Delta\theta_y$ ) that our system can detect. Since the drift length is 2 m, a 20  $\mu\text{rad}$  kick produces an offset of 40  $\mu\text{m}$  at WB-ZBPM, an amount equal to our resolution. Finally, solving Equation 4 for  $W'_{\perp,1}(t)$  gives a minimum measurable dipole transverse wake function per unit length of 0.1 V/pC/m/mm.

## CONCLUSION

We have presented a conceptual, zero<sup>th</sup> order design for a compact wakefield measurement facility. This facility can measure both the longitudinal and transverse wake functions with state of the art precision. Our estimates show that we can measure a minimum measurable monopole longitudinal wake function of 2.5 V/pC/m and a minimum measurable dipole transverse wake function of 0.1 V/pC/m/mm. The Argonne Wakefield Accelerator facility at ANL could be used to build a prototype version of this facility to prove the validity of this concept.

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