

RF phase stabilization for RF photocathode gun through electro-optical monitoring\*

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ABSTRACT

An electro-optical technique is being developed at the Brookhaven National Laboratory (BNL), Accelerator Test Facility (ATF) to monitor and control the phase of the photocathode laser beam with respect to the RF drive field for the RF photocathode gun. This technique utilizes the RF field induced birefringence which is probed by the photocathode laser beam. A proof-of-principle experiment has been performed using the ATF RF photocathode gun injection system for the linac.

INTRODUCTION

Radio frequency (RF) electron gun<sup>1,2</sup> has been developed to produce high brightness electron beam for free electron laser, high energy linear collider, and other applications. The strong electric field in the RF gun cavity accelerates the electrons rapidly, and hence reduces the space charge effect. Photocathode RF gun utilizing high frequency RF field can produce low electron emittance beam by using picosecond photocathode laser pulse to minimize the time dependent RF effect<sup>3</sup>. However precise timing of the laser pulse with respect to the gun RF drive field has to be maintained to stabilize the beam emittance and energy. Changes in the phase between the RF field and the laser pulse can be caused by drift and changes in the RF and laser system and have been observed in RF photocathode injection system. Such changes when uncorrected can be problematic for applications which require a stable electron beam. Therefore it is important that the phase between the RF field and the laser pulse can be measured so that corrections can be made when needed. Conventional electronic phase measurement techniques are not very useful because of their relatively narrow bandwidth, the low duty cycle often encountered in the measurement, and the techniques themselves are often sensitive to phase instability. To overcome these difficulties, we have devised an electro-optical (EO) technique to measure and control the phase between the gun RF field and the photocathode laser pulse.

EO techniques have been applied successfully in the measurement of pulsed RF field<sup>4</sup>. One of the most obvious advantages of the electro-optical techniques based on the Pockels and Kerr effect is their wide bandwidth. For example, the intrinsic response time of a Kerr fluid is in the order of picosecond. However, the general practice of placing the EO medium in between electrodes reduces the bandwidth due to the associated capacitance. In the case of high power RF measurement, the electrodes also introduce the possibility of electrical breakdown. In our technique, we use a bare EO crystal and place it inside a high power copper RF waveguide. RF field is sent through this waveguide and it induces a voltage across the crystal, generating birefringence in it. To measure the phase of the laser pulse relative to the RF field, one can send a portion of that laser pulse through the crystal and measure the resulting phase retardation in the different polarization components of the laser beam.

PRINCIPLE OF TECHNIQUE

Our technique is very similar to the conventional laser modulator technique using longitudinal Pockels cells. In these Pockels cells, the electric field is applied parallel to the EO crystal optical axis, and in the same direction as the incident laser beam. A portion of the photocathode laser pulse is sent through a linear polarizer before it is transmitted through the EO crystal housed inside the waveguide. The direction of polarization of the laser beam is at 45° with respect to the electrically induced birefringent axes of the crystal. A 1/4-wave plate followed by a second polarizer oriented at 90° with respect to the first polarizer are placed on the output side of the EO crystal outside the waveguide. The net effect of the RF field is to introduce additional phase retardation in one of the two orthogonal components of the beam along the electrical birefringent

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axis of the EO crystal. The amount of phase retardation is proportional to the amplitude of the RF field and it causes the transmitted beam to be elliptically polarized. The function of the 1/4-wave plate is to introduce an additional 90° phase retardation in one of the component of the beam so that in the absence of the RF electric field, the laser beam polarization will be changed from linear to circular. The circularly polarized laser beam will then be split by the analyzing polarizer into two beams with equal intensity which is equal to half the intensity of the input beam. This put the operating point at the 50% optical bias.

For a modulation voltage  $V_m \sin(\omega t)$  applied across the crystal, the two output beam intensities,  $I_1$  and  $I_2$ , are related to the input beam intensity  $I_0$  by<sup>5</sup>

$$I_1 = I_0 \sin^2[\pi/4 + aV_m \sin(\omega t)] \quad (1)$$

$$I_2 = I_0 \cos^2[\pi/4 + aV_m \sin(\omega t)] \quad (2)$$

where  $a$  is a constant dependent on the properties of the EO crystal and  $\omega$  is the angular frequency of the RF field. Hence,

$$2aV_m \sin(\omega t) = \cos^{-1} [\sqrt{(I_2 - I_1)/I_0} - \pi/2] \quad (3)$$

It is evident that one can measure, on one hand, the frequency of the RF field using a fast detector and a CW laser<sup>6</sup>. On the other hand, using a short laser pulse with pulse duration  $\ll 2\pi/\omega$ , one can measure the phase delay  $\omega t$  between the laser pulse and the RF field if the amplitude of the phase modulation  $2aV_m$  is measured. The amplitude of the modulation in phase retardation can be measured by monitoring the changes in the phase retardation in the probe laser beam as the phase between the laser pulse and the RF field is changed by over  $2\pi$  at constant RF power. Such a phase delay measurement is also needed to determine the exact amount of optical bias or the zero-crossing phase retardation introduced by the 1/4-wave plate.

### EXPERIMENT

A proof of principle experiment was performed at ATF to demonstrate the feasibility of this technique in measuring the phase between a RF field and a short laser pulse. A schematic of the experimental layout is shown in Fig.1. A z-cut

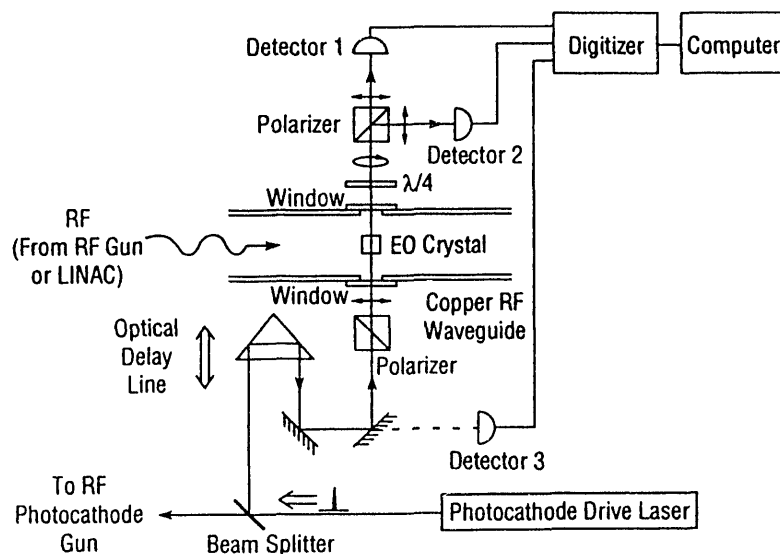


Fig.1. Schematic of the experimental layout.

1 cm(L) x 0.5 cm(W) x 0.5 cm(H) KD\*P crystal supported on a 0.5 cm diameter teflon rod was held in the middle of a 3 in. x 1.3 in. hollow section of copper waveguide with the 1 cm length of the crystal parallel to the 1.3 in. wall of the waveguide. This location and orientation of the crystal placed the crystal at the peak of the  $TM_{01}$  field pattern of the waveguide mode with the field parallel to the optical axis of the crystal. This waveguide and EO crystal assembly was positioned between two crossed prism polarizers and a 1/4-wave plate. Two small openings (0.25 in. in diameter) fitted with fused silica window were made on opposite walls of the copper waveguide to allow the passage of the laser beam through the EO crystal in the same direction of the RF field and the crystal optical axis.

The 2.86 GHz S band RF field was coupled out from the ATF photocathode RF gun drive via copper waveguide coupler and sent through the waveguide section. This RF field has a  $\sim 2$  us. duration and a peak power of  $\sim 10$  KW. Reflection of the RF power in the waveguide due to the presence of the EO crystal and its support structure was less than 20dB. The power of the RF pulse during the experiment was monitor using directional coupler and RF diode with the output of the diode fed to digitizer and computer for data processing. About 0.5% of the frequency-doubled output of the Nd:YAG photocathode drive laser at 0.5 um. was split off by beam splitter and used in our experiment. This laser pulse had a (FWHM) pulse width of about 15 ps. and a pulse energy of about 10 uJ.

In order to scan the phase delay between the RF field and the laser pulse so that the magnitude of the modulation in phase retardation induced by the RF field on the laser beam, and the zero-crossing phase retardation offset can be determined, the laser beam was sent through an optical delay line consisting of a right-angled prism and steering mirrors before it arrived at the first polarizer. The relative phase of the laser and the RF field was changed by an amount of  $\Delta\phi = 2\pi l/c$  when the prism was moved over a distance of  $l$ , assuming there is no drift or other changes in either the phase of the RF field and the laser pulse. To cause a  $2\pi$  change in the relative phase between the laser and the RF field, the prism has to be moved over a distance of  $l = 5.25$  cm for the 2.86 GHz RF field.

Three photon detectors (EG&G FND 100 photodiodes) were used in our experiment. Detector 1 and 2 (see Fig.1) were used to measure the intensities of the two orthogonally polarized components of the output beam from the analyzing polarizer,  $I_1$  and  $I_2$  respectively. The third detector monitored the input laser pulse intensity  $I_0$  energy for normalization purpose. The output of all the photodiodes was fed to digitizer and computer. We measured the quantities  $I_0$ ,  $I_1$ ,  $I_2$  as a function of  $l$  at a given RF power. The experiment was repeated for different RF powers.

## RESULT AND DISCUSSION

We found that the phase retardation induced in laser beam by the RF field at a given RF power level, adjusted for the zero-crossing phase retardation offset, varies sinusoidally with the distance  $l$  moved by the prism in the optical delay line, in good agreement with Eqn.(3). A typical result is plotted in Fig. 2.

From the sinusoidal fit of the measured phase retardation induced in the laser beam by the RF field as a function of the optical delay in the laser beam, one can determine the frequency of the RF field, the modulation amplitude of the phase retardation, and the optical bias or phase retardation zero-crossing (the offset from  $\pi/2$ ) introduced by the 1/4-wave plate. The modulation amplitudes of the electro-optically induced phase retardation were plotted against RF field amplitudes in Fig.3. Our results show that the amplitude of the phase retardation modulation is proportional to the RF field amplitude, confirming that the phase retardation is electro-optically induced by the RF field.

Based on the preliminary data we have obtained to date, we find that our best accuracy in determining relative phase between the RF field and the laser pulse was better than  $\pm 2^\circ$  or  $\pm 2$ ps., limited only by the noise in our detection system. It should be pointed out that our technique is not sensitive to fluctuation in laser pulse energy. Most of the uncertainty was caused by the jitter or random fluctuation in the phase of the RF and/or laser system. With a well calibrated and low noise system, one can, in principle, measure the relative phase between the RF field and the laser pulse with much higher accuracy. Efforts are being made to reduce the noise in our system and to improve the accuracy of measurement.

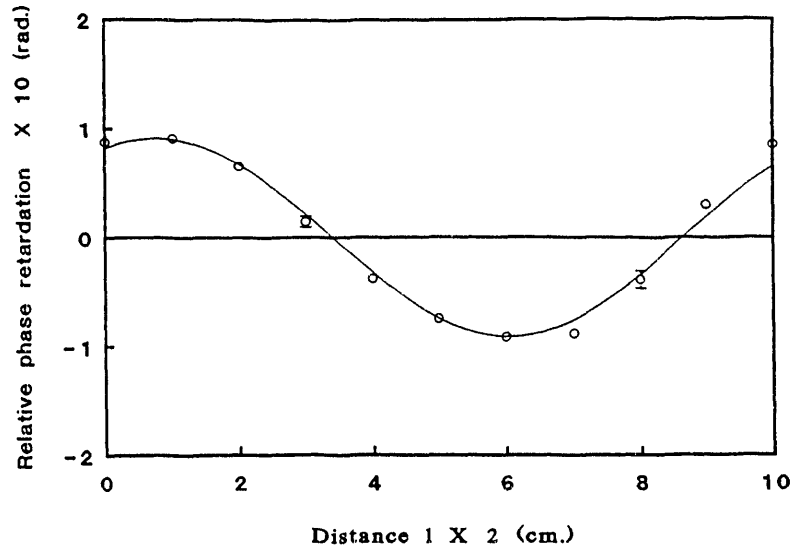


Fig. 2. Relative phase retardation induced by the RF field in the laser beam as a function of the distance moved by the right angled prism in the optical delay line. The curve is  $0.91\sin[2\pi(3.4-2l)/10.5]$ .

To use this technique to measure the phase between the RF field and laser pulse, one has to determine first the amplitude of the modulation in phase retardation, the phase retardation zero-crossing offset introduced by the 1/4-wave plate using the steps described above. One can then set the phase of the RF and laser system to the desired operation point before setting the optical delay for the probe laser beam to bring the phase retardation to the zero-crossing offset point. By maintaining the phase retardation at this set point at a given RF power, one can maintain the relative phase between the RF field and the laser pulse.

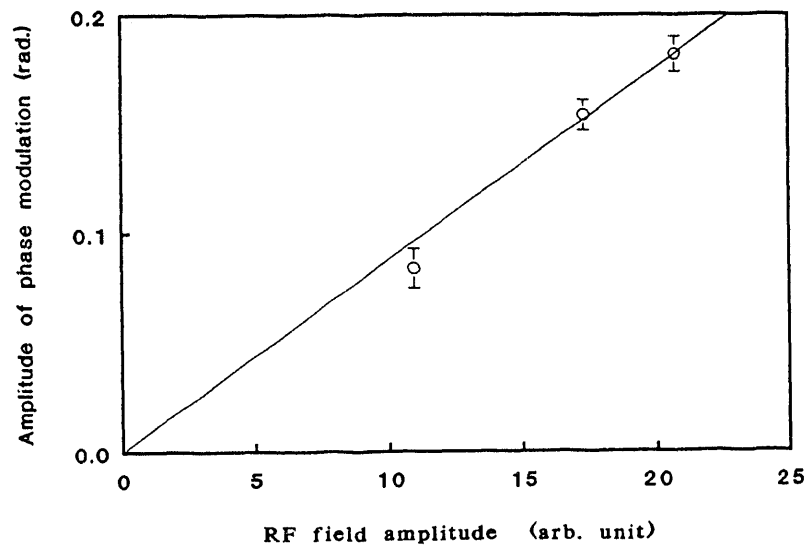


Fig. 3 The amplitude of the modulation in phase retardation induced in the laser beam by the RF field as a function of RF field amplitude.

## CONCLUSION

An electro-optical technique to measure the relative phase between a RF field and a short laser pulse based on the measurement of the phase retardation induced by RF field on the laser beam has been demonstrated. It can be used to measure and stabilize the relative phase between the RF drive field and the photocathode laser pulse in a RF photocathode injection system for the linac. Efforts are being made to improve the accuracy of this technique.

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