A PROTOTYPE OPTICAL VOLTAGE SENSOR FOR ACCELERATOR DIAGNOSTIC APPLICATIONS*

M. A. Brubaker+, C. P. Yakymyshyn++, A. J. Iverson++ and I. E. VandeVeegaete++

Abstract

A bulk electro-optic Pockels cell has been designed and tested for non-invasive monitoring of an electron beam or high-voltage conductor. This sensor directly measures the signal of interest rather than the time derivative and is thus attractive for long-pulse applications in the microsecond regime with slow rise times. Additional advantages include a fast response time on the order of 10 ns, low cost and complete galvanic isolation via optical fiber coupling between the sensor and electronics. The Pockels cell modulates the intensity of incident laser light as a function of voltage induced on a discrete electrode which is capacitively coupled to the high-voltage source. Details of the sensor design are presented along with preliminary measurements of a high-current electron beam using a BGO Pockels cell and 850 nm laser diode source.

I. INTRODUCTION

The DARHT II accelerator currently under construction at Los Alamos National Laboratory will provide a 2 kA current pulse with a duration in excess of 2 μs. This pulse duration is more than 30 times that of the DARHT I accelerator and thus requires different diagnostics for electron beam and pulsed power monitoring. Reduced rates of change combined with substantially longer integration times will provide a challenge for conventional B-dot probes. Furthermore, problems may be encountered with ground loops since time isolation is not practical for the DARHT II pulse length.

Electro-optic and magneto-optic sensors offer significant advantages for long-pulse applications. Both technologies have been demonstrated in the electric utility industry [1] and are readily adaptable to pulsed-power and electron beam measurements. Galvanic isolation eliminates ground loop problems through the use of fiber optic cables that link the probe, light source and receiver. Sensors based on the Pockels and Faraday effects measure electric and magnetic fields respectively with no dependence upon the rate of change. Such sensors can operate over a wide bandwidth with the capability to measure accurately at very low frequencies.

This paper describes a prototype Pockels cell sensor that is under development for pulsed-power and electron beam position monitoring on the DARHT II accelerator. Details of the design are presented and the principle of operation is explained. Preliminary data is provided for bench calibration and electron beam measurements. The optical voltage sensor is demonstrated to provide good results for pulses in both the DARHT I and DARHT II time scales.

II. PROBE DESIGN

The prototype optical voltage sensor utilizes the Pockels effect in an electo-optic crystal having ($\bar{4}$ 3 m) cubic symmetry. Each orthogonal component of linearly polarized laser light incident upon the crystal experiences a different index of refraction as a function of the applied electric field. The total accumulated phase difference between the fast and slow axes is thus proportional to the line integral of the electric field or the voltage applied across the Pockels cell. Passing the light exiting the cell through a suitable polarizer provides an intensity-modulated representation of the voltage. A more complete discussion of the Pockels cell is provided in a previous publication [1].

The Pockels cell described above is incorporated into a complete sensor as illustrated in Figure 1. A suitable electro-optic crystal is mounted to a glass substrate coated with ITO that provides an optically clear ground plane. The glass window also provides a convenient means for achieving a hermetic O-ring seal between outside air and the medium (e.g. vacuum) of the system. An aluminum pickup electrode one centimeter in diameter is attached to the top of the crystal to establish a capacitive voltage divider. This electrode is diamond turned on the side that bonds to the crystal to form a highly reflective mirror.

An optical fiber is utilized to launch and receive light from the sensor through a collimator assembly bonded to the outside surface of the glass window. A polarizer and waveplate are inserted between the collimator and window to obtain the desired modulation response. An eighth-wave plate provides a quadrature bias that is optimal for linear detection of relatively small signals. Under these conditions, incident light makes two

* Work performed under the auspices of the United States Department of Energy.
+ Los Alamos National Laboratory, Mail Stop P939, Los Alamos, NM 87545.
++ Dept. of Electrical and Computer Engineering, Montana State University, 610 Cobleigh Hall, Bozeman, MT, 59717

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1999	**N/A**	**-**

4. TITLE AND SUBTITLE
A Prototype Optical Voltage Sensor For Accelerator Diagnostic Applications

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Los Alamos National Laboratory, Mail Stop P939, Los Alamos, NM 87545

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT
A bulk electro-optic Pockels cell has been designed and tested for non-invasive monitoring of an electron beam or high-voltage conductor. This sensor directly measures the signal of interest rather than the time derivative and is thus attractive for long-pulse applications in the microsecond regime with slow rise times. Additional advantages include a fast response time on the order of 10 ns, low cost and complete galvanic isolation via optical fiber coupling between the sensor and electronics. The Pockels cell modulates the intensity of incident laser light as a function of voltage induced on a discrete electrode which is capacitively coupled to the high-voltage source. Details of the sensor design are presented along with preliminary measurements of a high-current electron beam using a BGO Pockels cell and 850 nm laser diode source.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

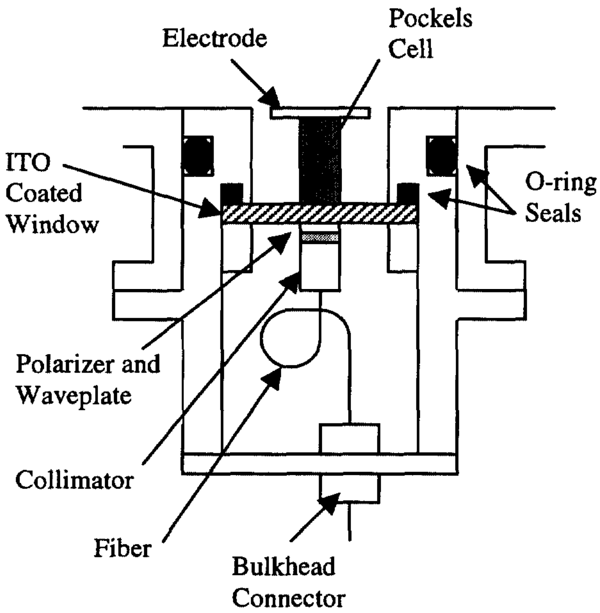

Figure 1. Illustration of optical voltage sensor design.

passes through the sensor and provides a linear output signal from the detector given by

$$V_{out} = P_{rec} G \left[2\pi \left(\frac{V}{V_\pi} \right) \right] \quad (1)$$

where P_{rec} (W) is the received optical power, G (V/W) is the gain of the detector and V (V) is the voltage applied to the Pockels cell electrode. The parameter V_π is a measure of modulation efficiency defined in terms of the optical wavelength λ (m), Pockels coefficient r_{41} (m/V) and refractive index n_o as

$$V_\pi = \frac{\lambda}{2 n_o^{\ 3} r_{41}}. \quad (2)$$

For this application, both $Bi_4Ge_3O_{12}$ and ZnSe crystals have been evaluated. At an operating wavelength of 850 nm, these materials exhibit V_π values of 46.5 kV and 9 kV respectively. Hence, both materials will provide a linear response for applied voltages on the order of 2 kV. While ZnSe is clearly more sensitive, BGO offers the advantages of demonstrated radiation hardness [2] and low conductivity.

The sensor configuration illustrated in Figure 1 was tested extensively using a 1x2 coupler to link a laser diode and receiver with the single 100/140 µm fiber connected to the sensor. However, minor problems with back reflections necessitated a slightly modified design with separate collimators and fibers for the launched and received signals. The new design provides better agreement with modulation predicted by equation (1).

III. BENCH CALIBRATION

Prototype sensors were calibrated using a special fixture that applied voltage pulses directly to the Pockels cell electrode. A local reference measurement was provided via a precision splitter and matching impedances were inserted as required by the time scale. This setup has been used to investigate optical voltage sensor response for the short pulse (DARHT I) and long pulse (DARHT II) regimes. These experiments were performed using a 785 nm laser diode and a high-performance, low-noise 100 MHz receiver developed specifically for this project with a prototype two-fiber BGO sensor.

A. Short Pulse

The DARHT I pulse has a rise time of under 20 ns and a full-width half-maximum of 70 ns. A representative waveform was applied to a prototype sensor using the pulse generator from the DARHT I calibration stand. The reference pulse and optical voltage sensor outputs with 425 V applied are compared in Figure 2. Good agreement is obtained at this level which provides acceptable signal to noise ratio for the optical sensor with a received power of 500 µW.

B. Long Pulse

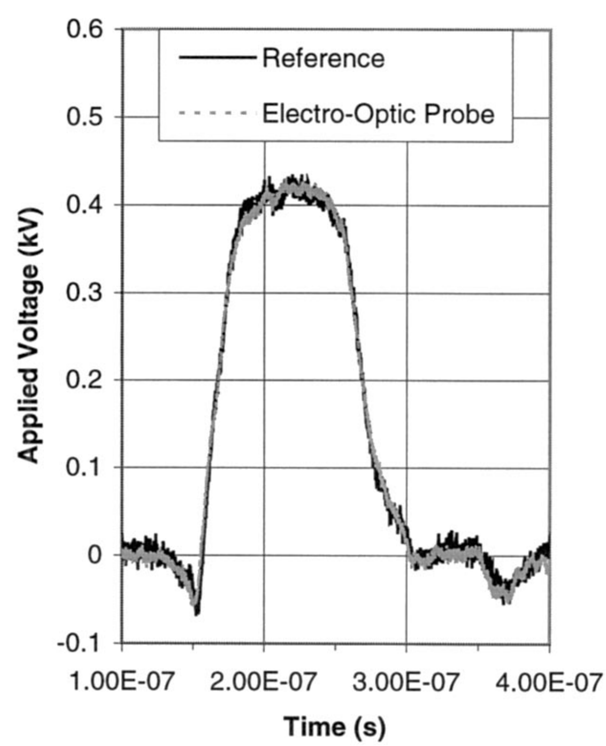

Figure 2. Electro-optic sensor response for short pulse.

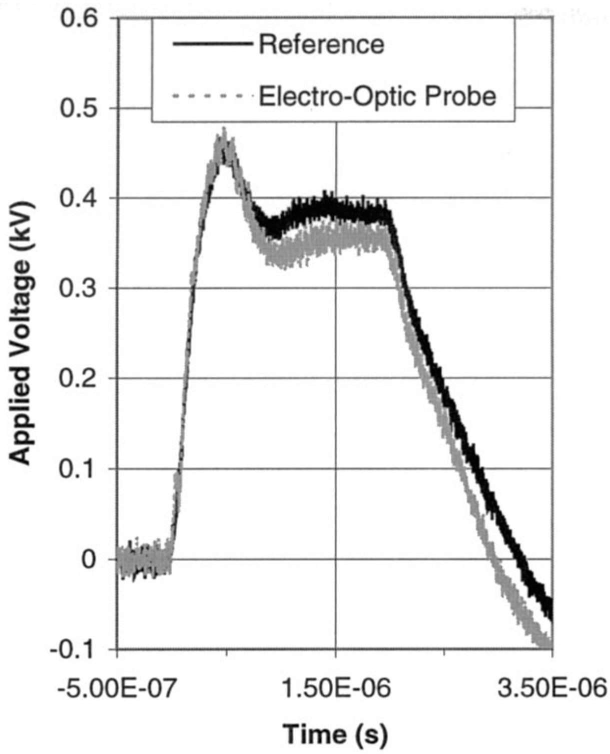

Figure 3. Electro-optic sensor response to a long pulse.

Similar measurements for a 2 μs pulse having a 200 ns rise time are presented in Figure 3. No changes were made to the experiment other than utilizing a different pulse generator. Good agreement is demonstrated during the rising edge of the pulse, but a discrepancy is clearly evident beyond 1 μs. The error is attributed to a resonant acoustic mode excited by a weak piezo-electric effect in the BGO Pockels cell. This acoustic mode has a resonant frequency near 500 kHz and creates additional birefringence in the crystal through the photo-elastic effect [3]. New prototype sensors that incorporate acoustic damping are currently under development to eliminate this problem.

IV. ELECTRON BEAM MEASUREMENTS

Prototype sensors of the single-fiber design have been tested on the DARHT I Integrated Test Stand (ITS) [4] using an 850 nm laser diode light source. This machine is a linear induction accelerator that produces a 70 ns pulse having a nominal current of 4 kA at 6 MeV. The optical voltage sensors were installed in a test spool mounted in a section of drift tube three meters downstream of the injector. An adjacent beam position monitor fitted with B-dot sensors (BPM #03 [4]) provided a reference measurement of the current pulse.

Multiple BGO and ZnSe sensors were installed during this series of experiments during which more than 500 shots were fired. All sensors were impacted by off-energy electrons from the head and tail of the beam which were over-focused in the test spool region. The BGO sensors provided repeatable responses and did not suffer any apparent damage from the electron impacts. With the laser sources deactivated, no received light was detected from the BGO sensors when the machine was fired. This indicates that scintillation due to electron impacts was not significant during these tests. Furthermore, the BGO crystals showed no evidence of transient darkening as no modulation was observed with the sensor electrodes shorted to ground.

In contrast to BGO, the ZnSe sensors were clearly affected by stray electron impacts. While these sensors worked as expected during bench calibrations before and after the accelerator experiments, they provided no signals when installed in the beam line. This is attributed to the fact that ZnSe is photoconductive [5] and thus acts like a short circuit after being hit by off-energy electrons.

The BGO sensors provided output signals which were comprised of the expected induced voltage on the pickup electrode superimposed upon an offset potential resulting from electron impacts. The electron impact signature was measured using an E-dot probe fitted with a fine screen to eliminate the induced signal from the beam. A comparison of typical BGO sensor, screened E-dot and B-dot measurements is presented in Figure 4 with all results referenced to beam current. Note that both the E-dot and B-dot signals were passively integrated prior to being digitized. The excessive noise observed on the

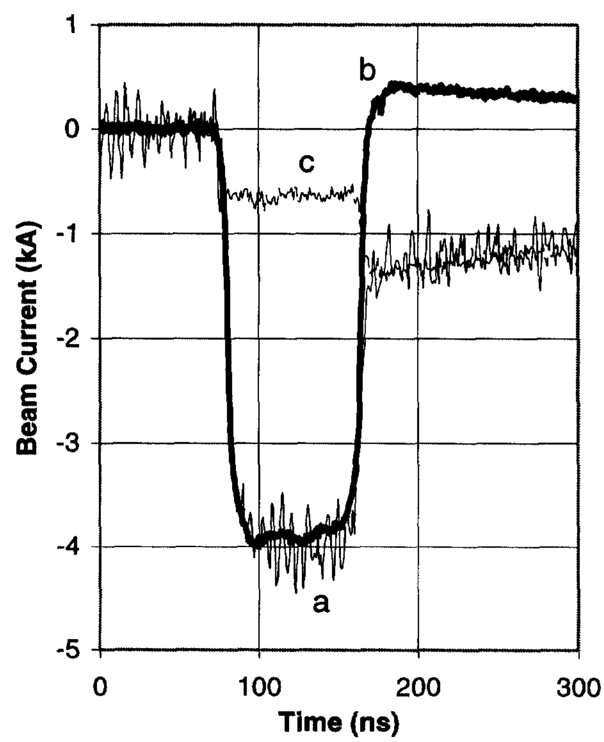

Figure 4. Comparison of (a) optical sensor, (b) B-dot and (c) screened E-dot outputs for a typical ITS shot.

optical sensor signal is attributed to the commercial receiver utilized for high frequency measurements during the ITS testing.

The induced portion of the optical sensor signal compares favorably with the integrated B-dot data. Note that the receiver was AC-coupled such that the residual DC bias on the sensor did not influence the response for subsequent shots. After sufficient charge accumulation, late time flashovers were observed to discharge the sensor electrode and thus prevent biasing out of the linear operating range. Bench calibration data taken before and after the ITS experiments agreed very well and demonstrated that the sensors were not adversely affected by the beam line environment.

V. CONCLUSIONS

A prototype BGO Pockels cell sensor has been demonstrated for both short (e.g. 70 ns) and long (e.g. 2 μs) voltage pulse applications. While excellent fidelity is obtained in the short pulse regime, minor calibration difficulties were encountered with long pulses. This problem results from acoustic resonance in the Pockels cell caused by a weak piezo-electric effect in BGO. Future designs will eliminate this problem through the incorporation of acoustic damping.

Preliminary experiments on the ITS indicate that BGO Pockels cells can survive in a beam line environment. Impacts from off-energy electrons were found to short circuit ZnSe sensors and apply a DC offset to BGO sensors. Accounting for the offset, the BGO probes provided reasonable agreement with conventional B-dots. The optical voltage probe remains under development for pulsed power and electron beam monitoring on DARHT II. Several solutions are currently being pursued to handle the unwanted signal resulting from electron impacts.

VI. ACKNOWLEDGEMENTS

The authors wish to thank D.C. Moir and the ITS operating crew for their invaluable assistance in testing sensors on the accelerator beam line. Montana State University gratefully acknowledges additional support from the DOE/EPSCOR program. In addition, we thank J. N. Downing, R. L. Carlson and C. A. Ekdahl for many helpful discussions and suggestions. Finally, we acknowledge Melissa Reed for her efforts in procurement and prototype electronics assembly.

VII. REFERENCES

[1] C. P. Yakymyshyn, M. A. Brubaker, P. M. Johnston and C. Reinbold, "Manufacturing Challenges of Optical Current and Voltage Sensors for Utility Applications," Invited Paper, Proceedings of the SPIE, Vol. 3201, October 1997, pp. 2-19.

[2] S. K. Sahu, K. C. Peng, H. C. Huang, C. H. Wang, Y. H. Chang, W. S. Hou, K. Ueno, F. I. Chou and Y. Y. Wei, "Radiation Hardness of Undoped BGO Crystals," Nuclear Instruments and Methods in Physics Research A, Vol. 388, 1997, pp. 144-148.

[3] A. Yariv and P. Yeh, *Optical Waves in Crystals*, Wiley, New York, 1984.

[4] P. Allison and D. C. Moir, "BBU Gain Measurements on the ITS-6 MeV, 4 kA Linac," Proceedings of the 1997 Particle Accelerator Conference, May 1997, pp. 1138-1140.

[5] A. Y. Elezzabi, H. Houtman and J. Meyer, "Time-Resolved Impact Ionization in ZnSe High-Voltage Switches," IEEE Transactions on Plasma Science, Vol. 22, No. 6, December 1994, pp. 1043-1047.