OPTICAL SENSORS FOR ACCELERATOR DIAGNOSTICS

Final Report for the period September 15, 1998 – September 14, 2001

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Optical Sensors for Accelerator Diagnostics

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Introduction

This report describes the efforts made over a three year period to address an urgent need for novel diagnostic sensors and systems to enable improved operation of the electron beam accelerator and imaging system known as DARHT currently being developed at the DOE's Los Alamos National Laboratory. DARHT is a key component of the DOE's Stockpile Stewardship Program.

DARHT system operation with increased pulsed duration is desired, creating the need for new sensor designs as compared with devices currently used in the existing short-pulse accelerator. This proposal investigated the development of new optical sensors and applied them to this particularly demanding need. This is the first time that optical sensing of pulsed electric fields in accelerator environments has been carried through to full system deployment, including radiation resistance, temperature effects and full beam position calibration using a conventional sensor calibration stand.

To date, over 200 sensors have been assembled and calibrated. The average error for these sensors in a beam position monitor application is ± 0.3 mm when mounted in a 125 mm radius beam pipe. This represents an error of 0.25%, which exceeds the performance targets for this program by a factor of four. Instantaneous accuracy is presently limited by shot noise in the system. Average pulse height calibration accuracy is currently limited by residual interferometric effects in the sensors and residual errors in the electronics caused by the simultaneous presence of automatic gain control offset errors and residual polarization modulation in the fiber cabling. The light source will be modified to eliminate these error sources, leading to shot noise limited system performance. This is anticipated to occur after full deployment of the system late this year.

Other DOE labs have expressed considerable interest in applying this technology to various beam-line diagnostic and pulsed power applications. For example, optical sensors for cell voltage monitoring at DARHT II are scheduled for deployment at LANL in late 2002.

E-field sensors

The first axis of DARHT provides an electron beam pulse having a full-width, half-maximum (FWHM) of 70 ns. The electron beam position and current are readily monitored using conventional B-dot probes with hardware integrators. Time isolation between the diagnostics and recording equipment is easily maintained using practical lengths of cable.

In contrast, the second axis of DARHT will provide an electron beam pulse exceeding 2 μ s (FWHM) in duration. This pulse length poses problems for time integration of B-dot probes and introduces the threat of ground loops since transit time isolation is no longer practical. A self-integrating electro-optic (EO) sensor offering complete galvanic isolation via optical fibers has been developed in response to these issues.

Electro-optic sensors based on the Pockels effect are gaining acceptance in the electric utility industry [1] where galvanic isolation of instrumentation is paramount. Such sensors offer advantages over conventional fiber optic links in both cost and performance. As illustrated in Fig. 1, the passive transducer element is installed on the accelerator, while the light source and receiver can be located remotely in a shielded area. EO sensors using $\text{Bi}_4\text{Ge}_3\text{O}_{12}$ (BGO) Pockels cells have been developed for both electron beam and pulsed power monitoring on the DARHT second axis accelerator. This paper provides an overview of the sensor designs for each application along with relevant data. The theory of operation of the Pockels cell has been previously described [1-4] and is omitted for the sake of brevity.

EO Sensor performance

The EO sensor is comprised of three primary components, namely a light source, sensor element and optical receiver as depicted in Fig. 1. Each component must be carefully optimized both individually and from the system perspective to obtain the best possible performance.

The EO sensor performance goals for electron beam and pulsed power monitoring are provided in Table 1. The former must meet the stated objectives for a current of 2 kA in bore sizes of both 10" (127 mm radius) and 14" (177.8 mm radius) while the latter must be achieved for a cell drive voltage of 200 kV. Note that practical limitations of available recording instruments may ultimately limit the sensor accuracy.

Application	Performance
Beam Position Monitor (BPM)	Position: $\pm 200 \mu\text{m}$ Current: $\Delta I < 2\%$ Bandwidth: 100 MHz
Cell Voltage Monitor (CVM)	Flatness: $\pm 0.5\%$ Absolute: $\pm 1\%$ Bandwidth: 100 MHz

Table 1. Performance goals for EO sensors.

Fig. 1. EO sensor implementation.

For the present application, the EO sensor Pockels cell is biased at quadrature using an eighth waveplate [3]. In this case, the general response of the sensor assuming linear operation in a dual-pass configuration will be

$$V_{\text{out}} = GP_{\text{DC}} \left(1 + 2\pi \frac{V}{V_{\pi}} \right) \quad (1)$$

where G is the receiver gain factor (V/W), P_{DC} is the optical power measured at the receiver (W), and V is the voltage induced on the Pockels cell (V). The parameter V_{π} is a measure of the Pockels cell efficiency given as

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

where λ is the optical wavelength (m), n_o is the bulk refractive index and r_{41} is the Pockels coefficient (m/V).

The EO sensor acts as a capacitive divider with a voltage induced upon the pickup electrode in response to the high voltage source of interest as shown in Fig. 1. The magnitude of the induced voltage is dictated by the ratio C_1/C_2 for $C_1 \ll C_2$. This ratio can be readily optimized for each application to ensure that the voltage is sufficient to provide adequate resolution without violating the criteria for linear operation ($V \ll V_{\pi}$). For BGO, V_{π} is on the order of 46 kV and 71 kV at respective operating wavelengths of 850 nm and 1319 nm.

The signal-to-noise ratio for the EO sensor is approximated using the second term of Eq. 1 in conjunction with the combination of various noise sources as

$$\frac{S}{N} = \frac{P_{\text{DC}} G \left(2\pi \frac{V}{V_{\pi}} \right)}{\sqrt{(P_{\text{shotnoise}})^2 + (P_{\text{receivernoise}})^2 + (P_{\text{lasernoise}})^2}} \quad (3)$$

Note that the noise terms are defined as root-mean-square (rms) values. The first term in the denominator represents the shot noise equivalent power for the photodetector and provides an indication of the theoretical limit. The remaining noise terms must be minimized by proper selection of the light source and receiver. Having defined the limiting parameters for the EO sensor, the optimization of the light source, sensor element and receiver may now be addressed.

Light Source

The ideal light source for the EO sensor would provide high optical power (> 5 mW) with very low relative intensity noise ($\text{RIN} < -140$ dB/Hz). Various commercial Fabry-Perot laser diodes offer high power levels up to 50 mW, but are quickly rejected for poor noise performance. At 850 nm, vertical cavity surface emitting lasers (VCSEL's) provide significantly better noise characteristics ($\text{RIN} < -125$ dB/Hz) at up to 10 mW. Light emitting diodes (LED's) offer excellent noise performance at 850 nm, but suffer from minimal power levels (< 1 mW).

At 1319 nm, distributed feedback (DFB) lasers provide acceptable power levels, but are difficult to stabilize for consistently low noise levels. Edge emitting LED's at this wavelength do not provide sufficient optical power and well above the shot noise limit. The most attractive option at 1319 nm is a diode-pumped YAG non-planar ring laser which offers very high power (> 200 mW) with extremely low noise levels ($\text{RIN} < -160$ dB/Hz).

The choice of light source (and operating wavelength) is thus narrowed to the 850 nm VCSEL and the 1319 nm YAG laser. The latter device was ultimately selected for superior noise performance and completely eliminates the laser noise term from the denominator of Eq. 3. A single laser can fanned-out using fiber optic couplers to drive multiple sensors and the amortized cost is actually comparable to using one VCSEL per sensor. However, this laser introduces additional difficulties, including a very narrow line width leading to interferometric effects and an extremely long coherence length that causes unwanted residual polarization problems.

When implemented using a 1319 nm ring laser, the noise floor increase due to the presence of the DC background created by the laser source is difficult to distinguish. As shown in Figure 2, the noise floor with the laser on varies with the square root of the received optical power, and is only slightly higher than the noise with the light source off. This measurement was made using approximately 500 μW at the receiver, which was the design power for the system. These results indicate that the receiver noise floor is low enough, and that the laser noise floor is basically shot noise limited.

Sensor Element

A common Pockels cell design illustrated in Fig. 3 is used for both monitoring applications. The physical scale may be considered in terms of the BGO crystal, which is 10 mm long and 3.5 mm in diameter. The details of each specific sensor envelope are addressed in later sections.

A borosilicate window serves as the substrate for mounting the BGO crystal and external optics. The BGO crystals are received polished to length and sent out to have anti-reflective (AR) and highly-reflective (HR) coatings applied. The former coating is necessary to minimize back reflections in the system while the latter provides the mirror required for dual-pass operation. The AR-coated end of the BGO is bonded to the

Figure 2- Receiver output greatly magnified in the vertical axis to illustrate noise floor with light source off (bottom trace) and light source on (top trace). The applied test pulse is extends well beyond the top of the image.

Figure 3- Schematic diagram of E-field sensor.

window substrate using epoxy and a silver epoxy electrode is applied to the HR-coated end. The entire BGO crystal is then potted in a composite of epoxy and yttrium aluminum garnet (YAG) powder, which secures a copper sheet ground plane to the window surface.

The potting is required to combat a weak photo-elastic effect in the BGO crystal that creates unwanted strain birefringence when an electric field is applied [5]. The YAG/epoxy blend is selected to provide a lossy medium that matches the acoustic impedance of BGO. This approach substantially reduces the acoustic error of the EO sensor, which varies with the spectral content of the applied field and can be problematic for the time scale of interest. Examples of the sensor response to an applied pulse without the damping material is shown in Figure 4. After applying the damping material, the response improves to that shown in Figure 5.

Figure 4 - Sensor response without damping material applied.

Figure 5 - Sensor response with damping material applied.

The required eighth-wave plate and polarizing beam splitter cube are bonded to the other side of the window after proper rotational alignment to the BGO crystal. Collimators using quarter-pitch graded index (GRIN) lenses couple light between the sensor and input and output multi-mode optical fibers. A slight splaying of the collimators works with the AR-coating to minimize interferometry effects, which cause calibration variations with temperature and wavelength. Typical sensor insertion losses are -9 dB, which is quite acceptable recognizing that -6 dB is the theoretical limit accounting for only the polarizer attenuation.

Figure 6 shows the variations in the insertion loss of almost 100 sensors. The variations are indicative of an assembly process that is improving as the number of assembled units increases. The data in Figure 7 show the peak to peak errors induced in the calibration factor by interferometric effects in the sensor element. Because the beam makes two passes in the sensor, and the two ends of the sensing crystal are plane-parallel, the beam can interfere with itself, depending on the coherence length of the light source used. This interference effect is known as a Fabry-Perot effect. In the case of a two mirror cavity with one cavity having a high reflectance (as is the case here), the resulting effect is the Gires-Tournois effect. As the laser frequency is tuned through the resonance of this

cavity, the amount of modulation imparted on the DC optical signal varies. The amount of variation depends on the reflectance of the front mirror and the coherence time of the light source relative to the cavity lifetime of the sensor.

For the system used here, the light source coherence length is much longer than the photon lifetime within the sensor cavity, so interferometric effects can be strong. Initial sensors showed variations as large as a factor of 3 as the laser source frequency was tuned. To reduce the effect, two remedies were employed. First, the front surface of the BGO crystal was antireflection coated to reduce the front reflectance down to 0.1%. For example, the interferometric effect can be large even for small reflectances, as shown in Figure 8 for a reflectance of 1.5%. A reduction to 0.1% improves this, but only in a linear fashion. Thus, a 0.1% reflectance coating (which is difficult to do in this geometry) will only reduce the errors to $\pm 5\%$. This is not sufficient for the present application.

To further eliminate the effect, the spatial overlap of the beam entering the crystal and exiting the crystal was minimized by tilting the two fiber collimators. This created a beam angle of approx. 3 degrees in the sensing crystal. The resulting interferometric effect consisted of multiple fringes across the beam diameter, effectively reducing the total observed interferometric effect (in effect washing out the fringes). With both remedies in place, the results shown in Figure 7 are the result. These errors represent rms errors of $<0.5\%$, which is considered acceptable for initial deployment. Further improvements can be achieved by combining several laser sources tuned to fractional integer spacings relative to the Free Spectral Range of the sensor cavity. The approach was designed but not implemented in this project.

Insertion Loss of BPM EO sensors 8-16-01

Figure 6 - Insertion loss statistics of E-field sensors.

BPM EO Sensors Interferometry on Production Run

Figure 7 - Interferometric-induced error statistics of E-field sensors.

Figure 8- Variations in the calibration factor of an E-field sensor as a function of the light source frequency, for a front-mirror reflectance of 1.5%. Note the large errors caused by this effect.

Optical Receiver

An optical receiver was developed in-house to meet the EO sensor requirements. Using a commercially available components, shot-noise limited performance has been obtained up to 100 MHz. The production receiver utilizes surface mount technology and incorporates an automatic gain control to correct for changes in the optical received power such that the correct calibration is maintained.

H-field Sensors

Some portion of the project effort was devoted to investigating the use of high purity Yttrium Iron Garnet (YIG) single crystals as optical sensors for measuring magnetic fields associated with electron beams. Some preliminary data indicates that the YIG samples, which were laser seeded-pedestal grown, have an enhanced Verdet constant relative to the values reported in the literature. However, this effort was not emphasized when it became clear that small perturbations in the magnetic permeability of the beam pipe could cause beam distortions that may not be compensated by the steering and focusing magnets. YIG has a very large magnetic permeability of >1000 , and would therefore impose a large field perturbation as seen by the passing electron beam. Therefore, deployable sensors were not pursued, to allow more resources to be devoted to

the Electric field sensor prototypes. A sensor prototype response is shown in Figure 9 below.

Figure 9 - Response of a YIG optical sensor prototype to a pulsed magnetic field of approximately 10 Gauss peak. Top curve- current applied to test station; Bottom curve- sensor response.

Beam Position Monitor

Housing Design

The DARHT second axis accelerator has very strict vacuum requirements and all sensors will be checked to a maximum allowable leak rate of 1.7×10^{-8} torr/liters/second. The EO sensor was thus designed with a stainless steel vacuum housing (metal seal to beam line) and a brazed alumina feed-through for the pickup electrode as shown in Fig. 10. A spring-loaded pin is utilized to ensure a good electrical contact to the Pockels cell electrode. The Pockels cell window is captured by a counter-bored flange and held in place with nylon-tipped set screws. Excess fiber from the collimator pigtails is coiled in the air-side housing and bulkhead FC mating sleeves facilitate external connections. All of the fiber optic connectors are angle polished to eliminate back reflections. Finally, an external bias connection to the Pockels cell electrode is also provided. Up to 1 kV DC

can be applied to the electrode through a 500 M Ω resistor. The bias connection also provides a means of performing an in situ calibration of the EO sensor with a fast pulse source and reference.

Fig. 10 - EO sensor housing for beam position monitoring.

Calibration Results

Beam position monitors using four equally spaced EO sensors have been calibrated using the DARHT second axis calibration stand [6]. After modifying the EO sensor

design to eliminate interferometry errors, the calibration factor stability typically indicates a standard deviation of 1%. A representative measurement of the test line current waveform by an EO BPM in a 10" (127 mm radius) bore is compared against the reference current transformer in Fig. 11. Good agreement is obtained, but a small acoustic error (less than 2%) is still present in the EO sensor response. The induced voltage on the EO sensor electrodes will be on the order of 1.5 kV for this configuration which satisfies the criteria for linear operation.

Fig. 11 - EO sensor and reference current transformer waveform comparison on calibration stand.

For small displacements of the center conductor, the acoustic effect is common mode and the EO sensor array calculates the position to better than ± 500 microns as shown in Fig. 12. The position is calculated as the difference between opposite detectors normalized by the sum of the sensor outputs and multiplied by the pipe radius. Note that the effect of the non-zero radius of the inner conductor on the current centroid position has been corrected for in the analysis. The relative accuracy is found to be consistently better than $\pm 300 \mu\text{m}$ over the flat top of the pulse.

Fig. 12 - Computed versus actual conductor offset for EO sensor beam position monitor.

Beamline results

The sensor was placed into the beamline of an operating accelerator to evaluate the sensor's ability to detect beam, as well as its compatibility with the accelerator environment. The sensor's output was compared with a conventional E-dot and an integrated B-dot probe for reference. As can be seen in Figure 13, the E-field probe response is a combination of the beamline's induced charge, along with direct impact charge accumulation on the pickup electrode. Because the decay time constant of the Electro-optic sensor is very long (hours), the impact charges are almost perfectly integrated over the duration of the electron beam pulse. The noise floor of the sensor in this case is poor, because this data was taken before improvements to the light source were implemented. Nevertheless, the response of the sensor in the accelerator environment was sufficiently encouraging to warrant further development efforts towards deployment of this technology on DARHT II.

Figure 13 - Response of a prototype E-field sensor in an accelerator environment.

Cell Voltage Monitor

The cell voltage monitor sensor was an extension of the work originally proposed, and was added in place of more detailed studies on the Magnetic field sensors described above. The EO cell voltage monitor is mounted on an external compensation can where the cell ballast resistors are located. The sensor electrode observes the drive rod voltage through a polycarbonate nose having the same dielectric constant as the insulating oil. An O-ring fits in the grooved portion of the polycarbonate to form a piston seal with the diagnostic port. As illustrated in Fig. 14, the Pockels cell window is secured in a counter bore using a threaded ring. A contact spring connects the Pockels cell and pickup electrode. Similar to the beam position sensor, the excess fiber is stored in an external can fitted with a connector plate. All fiber optic connectors are angle polished to prevent back reflections that can cause interferometric effects in the fiber runs.

Fig. 14 - EO sensor design for cell voltage monitoring application.

Testing of EO cell voltage monitors is currently in progress at LANL using the accelerator cell production test stand. At nominal voltage (200 kV) the EO sensor pickup electrode is expected to reach an induced voltage of 3 kV, which is still within the linear range. Initial results indicate some disagreement between the EO sensor and compensation can resistive divider. Typical data at less than half of nominal voltage are presented in Fig. 15, which shows that the EO sensor predicts a faster front time. At higher voltages, the discrepancy becomes worse, approaching 10% at 200 kV. Possible explanations are a voltage dependence of the resistive divider and acoustic error in the EO sensor. Efforts are currently under way to resolve this issue.

Fig. 15 - Comparison of EO cell voltage monitor and resistive divider.

Conclusions

The results presented here indicate that the BPM sensors are approaching the goals specified in Table 1. The relative accuracy of the beam position measurement is on the order of ± 300 microns and is ultimately limited by the noise floor and acoustic differences between sensors. Filtering out the acoustic signature may reduce the latter effect. The absolute accuracy is currently at ± 500 microns and the fidelity of the current measurement is within 2%. The limiting factor for absolute position accuracy believed to be offset errors in the receiver gain control. This effect is aggravated by residual polarization due to the YAG laser coherence length, which can cause significant intensity fluctuations depending on the orientation relative to the sensor polarizers. Work is in progress to address this problem through high-speed modulation of the residual polarization.

The EO cell voltage monitor can provide the absolute accuracy specified in Table 1, but satisfaction of the flatness requirement cannot yet be proven. Work is in progress to resolve the discrepancies between the EO sensor and resistive divider pulse shapes. Capacitive E-dot probes may ultimately provide a better confirmation of the drive rod voltage subject to integration difficulties for this time scale. Acoustic error is expected to be the ultimate limitation for the EO sensor in this case. Recognizing that the acoustic mode exhibits a clear resonant frequency, the use of filtering should provide improved results.

This project addressed an urgent need for novel diagnostic sensors and systems to enable operation of DARHT (Dual Axis Radiographic Hydrodynamic Test) facility currently under construction at Los Alamos National Laboratory. DARHT is a key component of the stockpile stewardship program. LANL has selected the electro-optic diagnostic system for installation on DARHT-2 as a beamline monitor and on all pulsed power supplies. A total of 200 sensors are currently being installed. Calibration testing indicates a beam position resolution of <0.5 mm in a 10 inch diameter beam pipe.

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Personnel supported

One graduate student will receive an MS degree based on this effort. Four undergraduate students were involved in the project either as summer interns, research students or as part of their senior design project, a capstone course in the Electrical Engineering program.

To support the transfer of technology to LANL and Bechtel staff, two students received summer internships at LANL. One student spent an extended six month stay at LANL to complete testing on next generation sensor designs. Extensive interactions between LANL project contact Michael Brubaker and MSU personnel were critical to this project's success.