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BOXCAR PHOTOGRAPHY

By

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ABSTRACT

A simple, inexpensive diagnostic has been developed for time-resolved imaging of repetitive self-luminescent phenomena. An electro-optic birefringent ceramic shutter is employed to perform photographic sampling and yields time resolution of 100 μ sec. Methods of image enhancement in the presence of background light from a finite-contrast shutter are discussed. The system has been applied to the study of plasma evolution in the CDX device.

MASTER

I. INTRODUCTION

In the investigation of transient plasma phenomena, visual imaging is often a useful supplement to other macroscopic diagnostics. In hot plasmas, such observation gives information primarily about the plasma edge, while in cooler plasmas light may be emitted from the entire plasma volume. Information can be obtained from the spectrum of the emitted light, from its time history, and from its spatial localization. In particular, photographic imaging has long been utilized as a primary diagnostic of magnetically confined plasma boundaries.¹

When the time evolution of the plasma is of interest, a number of imaging techniques are available. If the relevant time scales are on the order of seconds, as is often the case with present-day tokamaks, a standard video or motion picture camera can provide significant information.² Many events, however, occur on faster time scales. For investigation of sub-millisecond plasma phenomena, high-speed motion picture cameras and image-intensified framing cameras have been used. Both techniques are quite expensive, and the latter, while capable of extremely fast time resolution, cannot directly provide a color image.

This paper describes a very simple and inexpensive diagnostic that has been recently devised to obtain time-resolved color or black-and-white images of a plasma with particular application to the Current Drive Experiment (CDX). The goal of the CDX is to investigate novel means of current drive via various forms of helicity injection. Initial experiments have studied formation of a plasma discharge by a circulating electron beam and subsequent current penetration and evolution of a tokamak-like field topology.³ The discharge is pulsed with a repetition rate of up to 10 Hz. and current penetration and evolution of the plasma shape occur with time scales on the order of milliseconds or less. Important information can be obtained by comparing the experimentally observed images with the plasma evolution predicted by a numerical MHD model.

II. DESIGN CONSIDERATIONS

The light available from a self-luminescent object (such as the CDX plasma) is insufficient, in many cases where a short exposure is desired, to adequately expose the particular image detector employed (typically photographic film or a solid-state array). An image intensifier can be used for light amplification at the expense of a loss of spectral information and a rather high cost. Since the CDX discharge can be reproducibly pulsed, our approach is simply to expose photographic film, on successive shots, to light from a selected time interval during the discharge until the film is sufficiently illuminated. The film can then be changed, a different time interval during the discharge selected, and the procedure repeated to obtain images of the plasma showing its evolution as a function of time. Since light from the same portion of many successive discharges is used to form one photographic image, the result represents an optical average of these shots and the approach is analogous to the electronic technique of boxcar integration;⁴ hence, we have termed this technique "boxcar photography."

This procedure requires a shutter which can be electronically triggered and which has adequately short opening and closing times (sub-millisecond resolution was desired for the CDX application). Although electromechanical shutters have been recently produced with effective exposure times as short as 0.25 msec, substantial timing jitter associated with the solenoid-triggered mechanisms prevents their use here. In addition, they cannot be repeatedly fired at rates of more than a few hertz. Liquid crystal shutters are rapidly evolving,⁵ but currently available products are too slow for the application considered here. Shutters using fluid suspensions of metallic dipoles aligned by electric fields have been developed by Marks,⁶ but are also currently too slow. Shutters can be constructed using an electrically controllable, optically birefringent material placed between crossed polarizers. Implementations such as the Kerr cell or Pockel cell⁷ can be switched in time scales of nanoseconds. Their primary drawbacks are a small useful angular aperture, relatively high cost, and the complexity of the drivers needed to provide pulses of multi-kilovolt amplitude.

The electro-optic shutter used for the CDX diagnostic was originally developed for flash-blindness protection goggles for pilots and is now commercially available.⁸ The device uses a transparent ceramic material (lanthanum-modified lead zirconate

titanate, or PLZT) which exhibits an electric-field-dependent optical birefringence.⁹ The material is manufactured in large wafers (1- and 2-inch diameter) with interdigital electrode arrays deposited on both surfaces in order to generate a uniform electric field in the ceramic. The wafer is sandwiched, as with a Kerr cell, between two linear polarizers whose axes are perpendicular, and the optic axis of the PLZT is oriented at 45 degrees with respect to the polarizer axes.

For the particular composition of PLZT used in this shutter, the effective birefringence (Δn) is a quadratic function of the applied electric field, and there is zero effective birefringence when the applied field (E) vanishes: $\Delta n = K\lambda E^2$, where K is the Kerr constant and λ is the wavelength of incident light. Therefore, with no applied voltage the shutter is essentially closed and residual transmission depends primarily on the polarizer quality. If the polarizers are ideal (providing perfect linear polarization for all wavelengths), then the ratio of the light intensity transmitted through the modulator assembly to the incident intensity is proportional to $\sin^2(\pi KTE^2)$, where T is the effective thickness of the birefringent layer and K is, in general, a function of λ .¹⁰ For a fixed incident wavelength, the transmission increases from zero with no applied field to a first maximum at an applied field of magnitude $E_m = (2KT)^{-1/2}$.

Over the range of visible wavelengths, E_m varies by some 30% for the shutter used here. Typically, E_m is chosen to maximize white-light transmission and this choice results in somewhat reduced transmission at the blue end of the spectrum. The field E_m is reached in these devices for applied voltages on the order of 400-700 V. The contrast ratio of the shutter (defined as the ratio between transmission of white light with applied field E_m and transmission with zero applied field) is approximately 2000, and absolute transmission at $E = E_m$ is approximately 15%.

III. EXPOSURE AND CONTRAST CONSIDERATIONS

The use of photographic film as an image detector requires that care be taken in the interpretation of the results. The eye is approximately a logarithmic detector, and film attempts to mimic this response. The reflected density of a developed print (the log of the ratio of intensity reflected from an unexposed portion to intensity

reflected from an exposed portion) has a total range of only ~ 1.5 for most papers,¹¹ and the range over which the density is a linear function of the log of the exposure is considerably smaller (~ 0.5). Thus the dynamic range over which a print can be used as an absolute measure of incident flux is at most ~ 30 , and then only if the characteristic curve of the film is accurately known. Much more sensitivity is obtained with the use of negative film and measurements of transmission rather than reflection (a dynamic range of ~ 1000 is then feasible).

Photographic film does not act as an ideal integrator of incident flux. As the intensity of incident light decreases, the effectiveness of forming a photographic latent image (in terms of photons absorbed per density increment on the developed film) also eventually decreases, i.e., the exposure (incident intensity $\times$ time) required to produce a constant density in the developed film is not independent of intensity. This is a statement of reciprocity failure which is related to the fact that formation of a latent image requires more than one photon to be absorbed by a particular grain in the film within a certain period.¹² In addition, a series of N exposures of intensity I_0 and duration t_0 , separated by time t_w , do not in general produce the same photographic effect as a single exposure of intensity I_0 and duration Nt_0 . This effect, known as the intermittency effect, is of importance in photographic sampling systems. It was found by Webb¹³ that the photographic effect of an intermittent exposure is identical (including reciprocity failure) to the effect of an exposure of duration $N(t_0 + t_w)$ and constant intensity $I_c = I_0 t_0 / (t_0 + t_w)$, provided the frequency of the intermittent exposure ($f_i = 1/(t_0 + t_w)$) exceeds a critical frequency of fusion, f_c (typically, $f_c \sim 0.1$ – 1 Hz¹⁴). A significant loss of sensitivity of the photographic system can therefore occur due to reciprocity failure even if the intensity during each individual exposure is high. Thus, if possible, the optical system should be designed so that the average intensity I_c is not in a range subject to reciprocity failure for the particular film used.

The contrast ratio of the shutter together with the film characteristics determine the ability to discern features in the final photographic image which arise from events occurring in the interval during which the shutter is open. For a shutter with finite contrast, if optical emission from the portion of the discharge during which the shutter is closed is sufficiently intense, the desired features may be obscured. This concern

becomes more serious when the ratio of the discharge duration to the exposure period becomes large or when imaging a portion of the discharge cycle which is much less intense than the remainder of the cycle.

The effect of the finite contrast of the PLZT shutter is that very low-level light from the nonsampled part of the discharge is incident on the film. If the leakage is of sufficient intensity, an image can be formed in regions of shadow on the primary image. Also, a sublatent image due to the leakage can, at the particular locations where it is produced, enhance the sensitivity of the film to formation of the primary image (the effect of *latensification*¹²) and thus, upon development, distort that image. It is desirable to arrange the intensities of light in the system so that light leakage through the closed shutter is further reduced in effectiveness for image formation through reciprocity failure (while the primary image is not).

The contrast ratio of 2000 specified for the shutter used here assumes that light is normally incident on the polarizers. The efficiency of polarization, and hence the contrast ratio, decreases as the angle of incidence (θ_i) increases from zero (normal incidence). For $\theta_i = 15$ degrees, the contrast ratio is on the order of 600. Hence limiting the numerical aperture of the optical system can be an important consideration.

Another method employed to limit the effects of a finite contrast shutter is simply to position an electromechanical shutter, with effectively infinite contrast, next to it. Such electrically triggered shutters are available with clear aperture diameters of 2.5 cm and exposure periods as short as 6 msec.¹⁵ With an adequate heatsink, they can be pulsed at rates of up to 30 Hz. In operation, the timing of the slow mechanical shutter is arranged so that its open period brackets the open period of the fast PLZT shutter.

III. IMPLEMENTATION AND OPERATION

A diagram of the diagnostic built for the CDX experiment is shown in Fig. 1. A standard 4x5 view camera¹⁶ is used to record the image as it allows convenient interchange of sheet and Polaroid film backs. The PLZT shutter is mounted in a light-tight phenolic housing with an adapter that screws into the camera lens. An

electromechanical shutter is in turn mounted to the phenolic housing. The camera views the plasma cross section tangentially through two mirrors placed in a vacuum chamber port, and, due to the long optical path length, a 300 mm focal length lens is used to provide adequate image size on the film. The signal to initiate the boxcar photography cycle (from a manual push button) enables a shot counter gate which allows the CDX discharge trigger pulses to pass to the subsequent electronics for a selected number of sequential shots.

The PLZT shutter appears electrically as a capacitance of approximately $0.02 \mu\text{F}$ in series with an equivalent electrode resistance of $\sim 25 \Omega$. The shutter driver must be able to provide relatively fast rise and fall times into this largely capacitive load. A schematic diagram of a high voltage pulse amplifier designed for this application is shown in Fig. 2. The input stage utilizes a VMOS FET inverter (Q1) and accepts TTL-level pulses. The output stage consists of two Darlington-connected high voltage transistor pairs. The pair directly driven by the FET (Q2, Q3) is an inverter and the other pair (Q4, Q5) acts as a follower. On the positive-going edge of the input pulse, the shutter capacitance is charged by the follower stage. When the input signal returns to zero, the Schottky barrier diode (D1) conducts and the shutter capacitance is discharged through the inverter portion of the output stage. The circuit is designed to operate at a low duty cycle. The $1 \text{ k}\Omega$ resistor in series with the high-voltage input limits the maximum current drawn, and the $2 \mu\text{F}$ capacitor provides the peak currents needed for fast rise and fall times. The input to the high voltage amplifier is a pulse of adjustable width that is synchronized and delayed with respect to the CDX discharge trigger. The time delay and the pulse width are adjustable in $10 \mu\text{sec}$ increments using inexpensive, commercially available modules.¹⁷

An example of the switching speed of the shutter and amplifier is shown in Fig. 3. Here a white light source (a DC-powered tungsten lamp) illuminated the shutter through a collimator, and a photomultiplier tube (rise time $< 1 \mu\text{sec}$) was used as a detector. The output from the detector and the voltage across the shutter are shown for three exposures of different widths. The rise time of the voltage signal is approximately $50 \mu\text{sec}$ and the fall time, $20 \mu\text{sec}$. The shutter optical closing time is also approximately $20 \mu\text{sec}$, but the opening time is significantly longer. The opening

characteristic appears to be a two-stage process, an effect which has been previously reported¹⁸ and which appears to be related to the establishment of birefringence in the ceramic. The initial rate of opening is rather fast (the shutter reaches 20% of its ultimate transmission within $\sim 40 \mu\text{sec}$) but subsequently the rate decreases considerably. The shutter attains some 66% of its ultimate transmission in about $600 \mu\text{sec}$ and requires several hundred msec to reach the final steady-state, fully open level shown in the figure.

In the application discussed here, a perfectly square shutter characteristic was not a requirement, and effective exposure times of less than $100 \mu\text{sec}$ were feasible at reduced contrast. For even shorter exposures, several techniques are possible. Laguna¹⁹ has demonstrated a method of charging a PLZT shutter with a constant current (rather than R-C exponential charging) which yielded a significant improvement, and Wolfram²⁰ has discussed the approach of overdriving the ceramic.

Using the techniques discussed earlier, the maximum ratio of the discharge length to the shutter open period for which contrast degradation is not significant can be increased. Experimental checks of image contamination due to finite shutter contrast should be performed, however, and the characteristics of the particular film in use must be considered. Since a plot of the relative log exposure versus optical density produced in a film is not linear but rather sigmoidal,¹² simply repeating a series of exposures with the shutter closed will not provide an accurate indication of contamination of the desired image by light from the rest of the discharge. For a more realistic test, the film should be exposed to a uniform source of light for a period sufficient to yield an optical density comparable to that in the experimental image. This will ensure that the sensitivity of the film to the low light levels penetrating the closed shutter is comparable to its value in the actual experiment. A subsequent series of exposures to the discharge made with the shutter closed should then correctly indicate if image contamination occurs.

The system described above has recently been used to provide the first indication of the formation of a tokamak-like plasma by electron beam injection in the CDX device.²¹ For this experiment, type 57 Polaroid print film was used, the shutter exposure period was $500 \mu\text{sec}$, and 100 successive discharges were used to produce the

images shown in Fig. 4. Since the plasma duration for each shot was only ~ 20 msec and the luminosity did not vary greatly during the shot, the contrast was adequate without need for an auxiliary shutter; no image contamination was discernable.

IV. CONCLUSION

A simple method for obtaining time-resolved pictures of self-luminescent objects which can be reproducibly triggered has been described. Implementation of the technique with an inexpensive PLZT electro-optic shutter can yield time resolution down to $100 \mu\text{sec}$. Photographic film was used for image detection in this system, but a CCD array could easily be substituted. The diagnostic has been applied to the study of plasma phenomena and may prove useful in other fields.

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FIGURE CAPTIONS

FIG. 1. Diagram of the boxcar photography diagnostic.

FIG. 2. Schematic diagram of the high-voltage PLZT shutter driver.

FIG. 3. Example of switching speed of the high-voltage amplifier and the corresponding optical transmission through the shutter. Signals from three exposures of different widths are superimposed.

FIG. 4. Photographs taken of the CDX discharge at different plasma currents (I_p) using the boxcar system. (a) $I_p = 10$ A. (b) $I_p = 50$ A. (c) $I_p = 330$ A.

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Fig. 1

Fig. 2

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Fig. 3

Fig. 4

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