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# Design of a new optical system for Alcator C-Mod motional Stark effect diagnostic[a)]

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The motional Stark effect (MSE) diagnostic on Alcator C-Mod uses an in-vessel optical system (five lenses and three mirrors) to relay polarized light to an external polarimeter because port access limitations on Alcator C-Mod preclude a direct view of the diagnostic beam. The system experiences unacceptable, spurious drifts of order several degrees in measured pitch angle over the course of a run day. Recent experiments illuminated the MSE diagnostic with polarized light of fixed orientation as heat was applied to various optical elements. A large change in measured angle was observed as two particular lenses were heated, indicating that thermal-stress-induced birefringence is a likely cause of the spurious variability. Several new optical designs have been evaluated to eliminate the affected in-vessel lenses and to replace the focusing they provide with curved mirrors; however, ray tracing calculations imply that this method is not feasible. A new approach is under consideration that utilizes *in situ* calibrations with in-vessel reference polarized light sources. *© 2008 American Institute of Physics.* [DOI: 10.1063/1.2953681]

## I. INTRODUCTION

The motional Stark effect (MSE) diagnostic system[1] in Alcator C-Mod is unique in that a large portion of the optical element system lies inside the vacuum vessel and is therefore exposed to the complicated heat transfer environment between the plasma and the vessel wall. Figure 1 illustrates the optical system layout of the C-Mod MSE diagnostic, indicating that five lenses and three mirrors lie inside the vacuum vessel. The lenses are made of SFL6 with low Verdet constant and the mirrors are dielectric coated to minimize differences in S/P reflectivity and phase shifts.

Recent in-vessel experiments show that the polarization angle measured by the MSE diagnostic is affected by stress-induced birefringence on the in-vessel lenses caused by the heating and cooling of the in-vessel optical canister. As illustrated in Fig. 2, the measured polarization angle changes as much as 30° as the canister temperature is varied 40 °C. Note that the spurious angle changes are larger and more localized (more channel dependent) on the L2 lens doublet than on the L3 doublet. This behavior is caused by the different focusing patterns at the two lens positions: light from the DNB is completely out of focus at the L3 position (nearly filling the lens), whereas it is nearly in focus at the L2 position, with the edge spatial channels focused near the periphery of L2 and channels near the center of MSE's field of view focused near the center of L2. Thus, the edge channels are affected most strongly and most promptly by heat penetration from the periphery. On the other hand, the rays are completely defocused on L3; so in the zeroth order, the thermal effect is averaged out although there are still some local variations.

The effect of thermal-stress-induced birefringence is also observed in spurious drifts in measured polarization angle over the course of a run day when the DNB is fired into a gas-filled torus with known TF and vertical fields. Figure 3 shows the radial profiles of the tokamak pitch angle measured by MSE in four identical beam-into-gas shots taken at various intervals during a run day. The temperature at the canister surface near the L2 lens doublet measured by four thermocouples (sampling interval ~1 min) dropped by about 30 °C between the first ("9 a.m.") and the second ("11 a.m.") shots. The change in polarization angle measured by MSE was large and also channel dependent, qualitatively consistent with the previous in-vessel heating observation. The canister surface temperature reached an approximate thermal equilibration by the time the last two shots were taken ("4:50 p.m." and "5:05 p.m.") and correspondingly the change in polarization angle measured by MSE was smaller.

## II. STUDY ON THE CURVED MIRRORS

Several new optical designs have been evaluated to remove the in-vessel lenses that suffer from the thermal-stress-induced birefringence and to replace the current flat mirrors with mirrors having appropriate curvature to provide the desired focusing. The first approach exploits the intrinsic astigmatism of spherical mirrors at non-normal incidence. If a sagittal focal line is vertical with respect to the horizontal midplane and its focal length is the distance between one MSE channel footprint and the spherical mirror, the viewing footprint will have a "line" radial resolution. In this configu-

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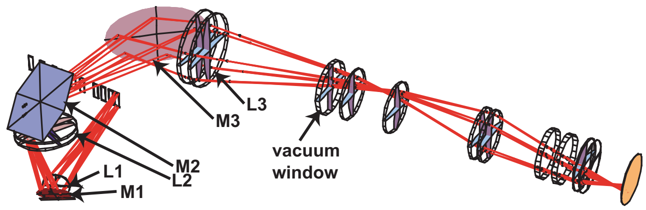


FIG. 1. (Color) Optical system layout of the MSE diagnostic in Alcator C-Mod. The small vertical rectangles are the footprints of the ten MSE channels along the diagnostic beam trajectory. A ray tracing example from the edgemost channel is given. All the elements are enclosed by the stainless steel tubes ("canister") which are not shown in the figure.

ration, each MSE channel has its own Rowland circle from one spherical mirror, providing a compact and lensless in-vessel focusing system. The limitation of this configuration is that the Rowland circle must be vertical, which is incompatible with the in-vessel MSE viewing geometry because the beam of rays reflected from the spherical mirror must have a radial component in addition to its vertical component in order for the second reflective element to reside outside the plasma. The vertical tilting angles of the Rowland circle with respect to the horizontal midplane are calculated for various different arrangements of the in-vessel mirrors by changing their locations and/or number. The calculations show that none of the configurations achieves tilting angles close to the required 90°.

The second approach utilizes two spherical mirrors in a particular arrangement[2] to provide wide angle "point-to-point" focusing. Since the Rowland circles from two spherical mirrors are coplanar in this concept whereas the MSE system requires the Rowland circles to be (close) perpendicular to each other, a new set of conditions that constructs the point-to-point focusing using two spherical mirrors whose Rowland circles are perpendicular to each other have been derived:

$$f_{s1}(f_{s2}-f_{m2})=(f_{s1}-f_{m1})(f_{s2}+f_{m1}-f_{m2}),$$

$$f_{m1}+f_{s2}=d,$$

$$f_{s1}>0, f_{s2}>0, \tag{1}$$

where $f_{s1}$ and $f_{m1}$ are the sagittal and meridional focal lengths of the first spherical mirrors, respectively, and $f_{s2}$ and $f_{m2}$ are the corresponding focal lengths for the second mirror. $d$ is the distance between the two mirrors. The second condition turns out to be unfavorable to the application of this concept to our problem. The size of the image on M2 is limited by the size of M2 itself which is already at its maximum (15 cm in height) because of the space limitation. Then the magnification factor is defined by the image size and the object size which in this case is the radial extension of the measurement along the diagnostic beam trajectory which must be long enough to reasonably cover the half the plasma minor radius to obtain meaningful radial profiles. The current C-Mod MSE system measures the pitch angles at ten different radial locations from 0.69 to 0.87 cm in major radius and this covers about 80% of the plasma minor radius. This gives the magnification factor $0.15/(0.87-0.69)=0.83$. The distance between the object and M1 ($f_{m1}$) being fixed as 35 cm, the magnification constrains the distance between M1 and M2 not be greater than 30 cm. However, the second condition in Eq. (1) requires the distance be greater than $f_{m1}$ which is already greater than the allowable maximum M1-M2 distance.

Due to the intrinsic limitations with spherical mirrors, the ray tracing calculations to optimize the shape of the mirror have been tried. The mechanical constraints and relative long distances require aberration correction to be maintained at each point in the system. Unfortunately, the optimized mirrors cannot correct coma and linear focus errors at the

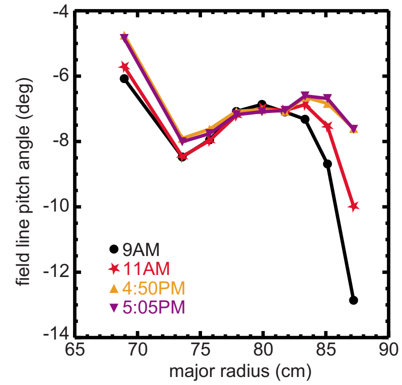


FIG. 3. (Color online) The tokamak pitch angle profiles from four beam-into-gas shots. All the shots have the same magnetic fields and gas pressure.

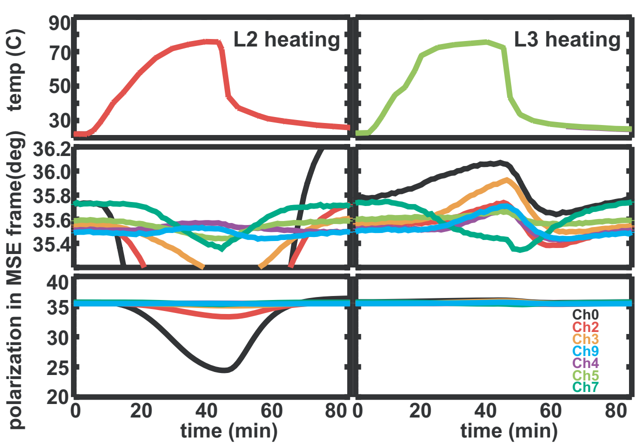


FIG. 2. (Color) In-vessel canister heating test results. The plots on the left column are for the L2 heating test and those on the right for the L3 heating. The top plots show the temperature variation over the experimental time. The second plots are the magnified version of the bottom plots. The channel numbers are written in the order of the tokamak major radius (Ch0, edge most; Ch7, core most).

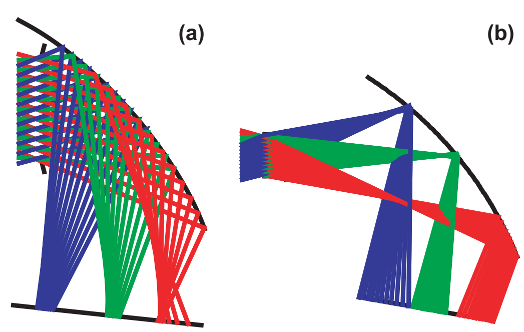


FIG. 4. (Color) Ray tracing results to find the optimized shape of the mirrors: (a) Optimized M1 without L1. (b) Optimized M2 without L2.

same time by removing the in-vessel lenses and allowing the mirrors to have curvatures. Figure 4 shows the results of the ray tracing. Figure 4(a) shows that the coma cannot be corrected with the optimized mirror M1 without L1 and Fig. 4(b) shows that the linear focus error cannot be corrected by curved M2 alone.

## III. *IN SITU* CALIBRATION METHOD

As discussed above, substituting curved mirrors for the combination of lenses and flat mirrors proves to be difficult and has many limitations. Therefore, an *in situ* calibration scheme is under consideration that would calibrate the MSE diagnostic by translating polarized light sources into the MSE field of view after each plasma shot. The effect of stress-induced birefringence on the polarization angle can be computed analytically using straightforward Mueller calculus by considering incident linearly polarized light on a simple waveplate with fast axis orientation ($\phi$) and retardance ($\varepsilon$). The polarization angle $\theta$ of the transmitted light is given by

$$\tan(2\theta) = \frac{\tan(2\gamma)[1-\cos^2(2\phi)(1-\cos\varepsilon)] + \sin(2\phi)\cos(2\phi)(1-\cos\varepsilon)}{\cos\varepsilon + \cos^2(2\phi)(1-\cos\varepsilon)[1+\tan(2\phi)\tan(2\gamma)]}, \tag{2}$$

where $\gamma$ is the input polarization angle. This relation implies that just two measurements of the reference polarizations are sufficient to characterize the effect of the thermal-stress-induced birefringence. Thus, by measuring the change in the polarization at two different polarization angles, one can uniquely determine both the phase shift and the angle of the fast axis, from which one can compute the change in polarization angle at any input polarization angle.

The overall design objective is to provide a calibration that is accurate to better than 0.2° in pitch angle, which requires an accuracy of better than 0.1° in the MSE frame of reference. If the calibration polarized light source were to wobble about its axis by some angle, the polarization angle of its light changes by the same amount. This places a very demanding requirement on the mechanical design of the translatable light source: it must retain its orientation, over a period of months, to approximately 0.1°.

This difficult requirement is avoided in an alternate scheme, shown in Fig. 5, that uses a fixed (nonmoving) polarized light source which is mounted on the MSE optics canister. The polarized light is reflected by a mirror that is translated into the MSE field of view after each shot. This scheme still requires that the polarized light source retain its orientation to better than 0.1° over a period of months, but this should not be difficult to achieve because the light source is firmly attached to the rugged MSE optics canister. Ray tracing calculations (Fig. 6) have identified an optimized mirror shape that can provide the full field of view from all the MSE channels with full angles by having the horizontally extended polarized light source on the both sides of the lens.

One difficulty in this concept is the effect on the polarization angle from reflection off the mirror at non-normal incidence, since there will be unavoidable errors in orienting the mirror. Figure 7 illustrates ray tracing calculations that examine this effect for ideal dielectric mirrors. The rate of change in the polarization angle before and after the reflection is about 5° per a degree of mirror vertical tilting. It is also observed that the rate of change is independent of the incident polarization angle by comparing Figs. 7(a) and 7(b) and further calculations show that the rate decreases as the angle of incidence increases. Analytic formulas based on Ref. 3 have been derived for the case where there is only vertical tilting of a mirror:

$$\tan\Delta\phi_p = \frac{\sin\theta\sin(2\varepsilon)\cos^2\varepsilon}{\tan^2\theta - \cos(2\varepsilon)\sin^2\varepsilon} \tag{3}$$

for ideal dielectric mirrors and

$$\Delta\phi_p = \pi - 2\phi_p + \tan^{-1}\left\{\frac{\sin\theta\tan\varepsilon[1+\sin^2\theta - \cos^2\theta\cos(2\varepsilon)]}{\tan^2\varepsilon[\sin^2\theta - \cos^2\theta\cos(2\varepsilon)] - \sin^2\theta}\right\} \tag{4}$$

for ideal metallic mirrors, where $\Delta\phi_p$ is the change in the polarization angle before and after the reflection, $\phi_p$ is the incident polarization, $\theta$ is the angle of incidence, and $\varepsilon$ is the vertical tilting angle of the mirror. These analytic expressions yield the same result as the ray tracing for the ideal dielectric mirrors. In addition, the analytic calculations show that the rate of change in the polarization is somewhat less for an ideal metallic mirror than for the dielectric mirror and that

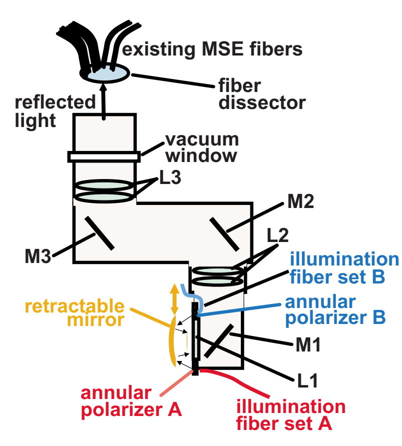


FIG. 5. (Color online) Proposed layout for an *in situ* calibration system for MSE on Alcator C-Mod. Linearly polarized light strikes a mirror that is slid in front of the plasma-facing lens (L1) shortly before and after a shot.

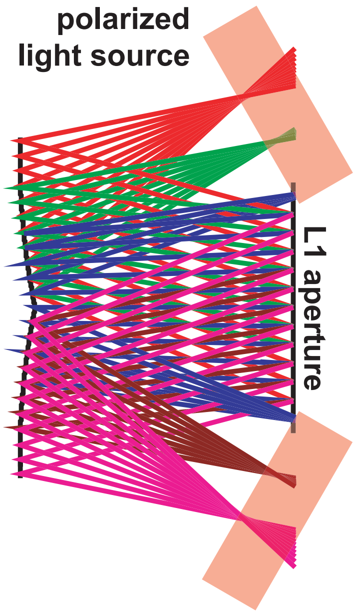


FIG. 6. (Color) Ray tracing calculations to optimize the retractable mirror shape to provide the full MSE field of view at all angles. The rays with different colors simulate those from the real light source from the beam from different channel locations.

the dependence on the angle of incidence is reversed: the change in polarization angle vanishes for small angles of incidence on metal mirrors. Nevertheless, the allowable tolerance in positioning the mirror is achievable only when the angle of incidence is less than about 14° for a metal mirror. Overall, this variation of polarization angle on reflection from a mirror significantly complicates the optical design of the *in situ* calibration system using a fixed polarized light source and a translated mirror.

A final optical design is under evaluation that positions a fixed annular polarized light source just in front of, and at the periphery of, the L1 lens. This configuration offers the distinct advantage of requiring no moving parts, at the cost of a small reduction in etendue during normal operation.

Several nonoptical approaches to eliminate the effect of stress-induced birefringence, or else to calibrate its effect on the measured polarization angle, are also possible. The most straightforward solution is to maintain the optics canister at fixed temperature, despite variations in its local thermal environment, by passing gas at constant temperature through a tube that is welded to the MSE in-vessel optics canister. This approach reduces temperature gradients in the MSE in-vessel lenses and thereby reduces spurious changes in polarization angle and can be used in parallel with *in situ* calibration techniques. One can also effectively calibrate the MSE diagnostic in real time by comparing its measured pitch angle

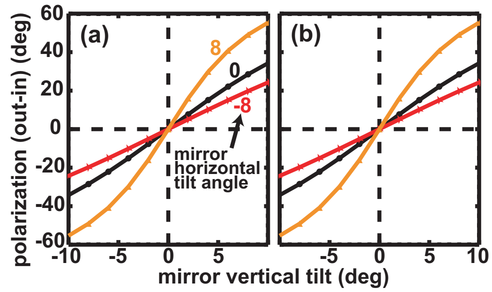


FIG. 7. (Color) Ray tracing calculation results for mirror tilting effect on the reflected polarization. The vertical axis is the difference between the incident and the reflected polarizations with the polarization of the incident light of (a) 80° and (b) 105°. The angle of incidence is 15° in both cases.

against magnetic reconstruction calculations (EFIT) at an Ohmic time in the discharge.[4] Initial comparisons of this approach during lower hybrid current drive experiments on C-Mod are promising.[5]

## IV. SUMMARY

The origin of shot-to-shot drift in the polarization angle measured by MSE on Alcator C-Mod has been traced to thermal-stress-induced birefringence on in-vessel lenses. Several solutions to overcome this problem have been evaluated. Substituting curved mirrors for the combination of the lens and the flat mirrors has intrinsic difficulties both in the magnification and in the aberrations. An *in situ* calibration scheme appears promising, but the requirement of 0.1° positional stability will be challenging. In the scheme using the retractable mirror and the fixed polarizer, both ray tracing and the analytic calculations show that small angular displacements of the mirror can generate surprisingly large change in the polarization angle of the reflected light. This work has revived interest in solutions based on thermal insulation and real-time calibration.

## ACKNOWLEDGMENTS

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