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Design of a multi-channel polarization-preserving optical system for the KSTAR motional Stark effect diagnostic

Kyuhang Lee [a,b], Jinseok Ko [c,d,*], Jae Heung Jo [b], Jinil Chung [c]

[a] General Optics Co., Bucheon 14441, Republic of Korea
[b] Hannam University, Daejeon 34430, Republic of Korea
[c] National Fusion Research Institute, Daejeon 34133, Republic of Korea
[d] University of Science and Technology, Daejeon 34113, Republic of Korea

HIGHLIGHTS

- Description on how the polarization control is accomplished in the complex optics for the KSTAR MSE system.
- Various quantitative analyses for the optical performance in accommodating multiple and tilted observation chords.
- Integration of the fabricated components including the fiber bundles and the dissector module for them. In-vessel testing for the image formation with the integrated optics system.

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ABSTRACT

An optical system capable of preserving, or minimizing the change of, the polarization properties of incident light has been designed and fabricated for the motional Stark effect diagnostic system which measures internal magnetic field structures inside the tokamak for the Korea Superconducting Tokamak Advanced Research. A dual photoelastic modulator (PEM) with a linear polarizer is included in the optical train with four lenses, a mirror and a dichroic beam splitter. Particular cares have been taken for the polarization properties of the delivered light to be perturbed as little as possible under a strong magnetic field and high vacuum. The lenses are made of STIH-6, a material with low Verdet constant, which minimizes the Faraday rotation. The residual Faraday rotation that takes place in the non-STIH-6 optical elements such as the vacuum window and the optical apertures of the PEM is calibrated out from the in-situ measurements using an in-vessel reference polarizer while energizing the magnetic field coils. In the lens design, the object plane is rotated by 44.8° from the optical axis because of the tilted setup-port. The image surface has a finite curvature to reduce the aberration from the four lenses. The fiber dissector is designed based on the focal plane that aligns the focal points from 25 lines-of-sight, each of which constitutes a bundle of 19 fibers. The fibers run about 35 m from the front optics in the tokamak vacuum vessel to the detector in the diagnostic area remote from the tokamak hall. The footprint images at the intersections of the lines-of-sight on the neutral beam trajectory confirms the imaging quality is sufficient to the diagnostic requirement with the designed magnifications.

1. Introduction

In the nuclear fusion research, toroidal plasmas in a device like a tokamak is confined by helical magnetic field lines formed by both external coils and the plasma itself. The rotational transform which is a measure of the amount of the poloidal turn over a single toroidal turn of the field line is an important factor to examine the stability [1], equilibrium [2], and transport [3–5] of the plasma. The reciprocal of the rotational transform, or safety factor, q, is often used for practical stability analyses and is a function of the magnetic field line pitch, and therefore, localized measurements of the magnetic field line pitch are a crucial piece of information to evaluate the profile of the safety factor since they provide the internal constraints in the magnetic equilibrium reconstruction. The most reliable method to diagnose the field line pitch is the motional Stark effect (MSE) diagnostic [6]. This diagnostic utilizes the polarized light from the Balmer-α emission from the energetic particles injected into the

* Corresponding author at: National Fusion Research Institute, Daejeon 34133, Republic of Korea.
E-mail address: jinseok@nfri.re.kr (J. Ko).

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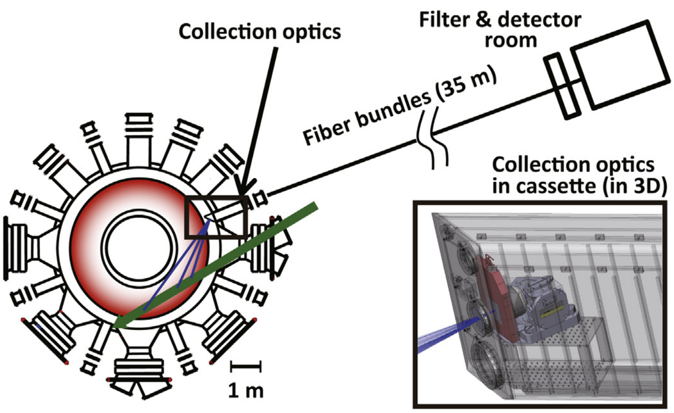

Fig. 1. Top view of the KSTAR tokamak vacuum vessel with the schematic of the MSE diagnostic system (The toroidal plasma is rendered in shaded red). The green line indicates the trajectory of the neutral beam that induces motional Stark effect after interacting with the plasma particles. The (three) blue lines roughly represent the lines-of-sight of the MSE system. The 3D-rendering view of the front optics housing in the cassette structure is also shown in the right-bottom box. The detailed structure in the front optics housing is given in Fig. 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

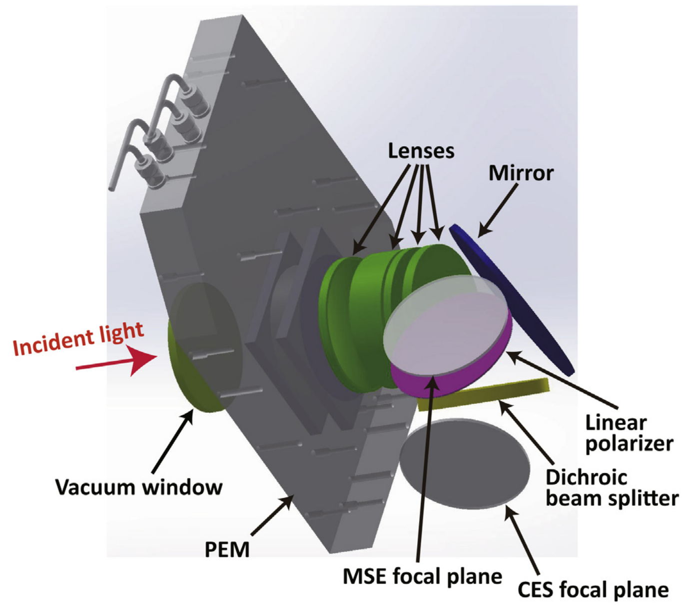

Fig. 2. Internal layout of the front optics for the KSTAR MSE system. MSE and CES focal planes are virtual.

plasma under Stark effect where the Lorentz electric field is induced by the local magnetic field in the frame of the moving particles [7].

The 25-channel MSE diagnostic system has been recently designed and installed in the tokamak device for the Korea Superconducting Tokamak Advanced Research (KSTAR) [8]. Fig. 1 shows the schematic of the KSTAR MSE system. The collection optics including the dual photoelastic modulator (PEM) resides in a long mechanical structure inserted into the vessel port as a 'cassette'. Also shown in Fig. 1 the three-dimensional rendering of the optical housing in the cassette. The intensity-modulated signals after passing through the dual PEM and the linear polarizer are transferred along the fiber bundles to the diagnostic room where there are the bandpass filters and APD detectors. The second-harmonic components of the two fundamental PEM frequencies (20 and 23 kHz) in the modulated signals contain the information on the linear polarization angle which is projected into the polarization angle of the Lorentz electric field. The relation between the Lorentz electric field and the magnetic field vector that is implemented in the magnetic equilibrium solver constrains the iterations of the equilibrium calculation to produce the magnetic pitch angle and other post-processed data.

Its initial operation results and discussions on the proof-of-principle physics experiments are reported in other literature [9,10]. The design of the APD detector and bandpass filter modules is also discussed in separate publications [8,11]. This article mainly describes the design and fabrication of the front optics system including the key features of its polarization-preserving capabilities under harsh (high magnetic field and extreme space constraints) conditions.

2. Polarization-preserving features

Fig. 2 illustrates the internal layout of the front optics. The MSE front optics is shared by another optical, but non-polarization, diagnostic (Charge Exchange Spectroscopy; CES). While the linear polarizer is an essential element in the MSE measurement, it may attenuate the signal intensity of the CES. Therefore, a dichroic beam splitter with its cutoff wavelength of 600 nm has been adopted to reflect off the MSE signals (>600 nm) and transmit the CES signals (<600 nm). The linear polarizer is then located above the beam splitter. The strong toroidal magnetic field has its component parallel to the optical axis in some part of the optics system. In order to minimize the Faraday rotation in such lens media, the lenses are made of STIH-6, a material with negligible Verdet constant ($0.08 \pm 0.17\,^{\circ}$/T cm at 656 nm) [12].

The residual Faraday rotation due to the non-STIH-6 optical elements (vacuum window and two PEM aperture windows – fused quartz and fused silica, respectively) is calibrated from the in-situ polarization measurements on the in-vessel reference polarizer installed at the viewing dump while the magnetic field is increasing or decreasing. An ideal structure as a 'reference' polarizer would have the features like the rotation flexibility of the linear polarization angle, the coverage of the viewing dumps of all the MSE sight lines, and the long-distance (about 2 m) collimation onto the object lens filling the inlet of the front optics. In this regard, the current reference polarizer module may not be ideal; The transmission axis of the polarizer is fixed (and close to being vertical) and the polarizer is located only near the viewing dump of the optical-axis sight lines. Although not ideal, its functionality as its present configuration is quite acceptable in the sense that the collimation is good enough to fill out the front optics and therefore, the polarized light signals including the in-direct ones (reflected from the torus structures, for instance) are collected almost uniformly over all the channels. The typical polarization angle from the plasma discharges, or the π polarization components from the motional Stark effect, is close to being vertical and this is the reason that the transmission axis of the polarizer is fixed that way.

The in-vessel reference polarizer has also been used to investigate the effect of stress-induced birefringence possibly imposed on the vacuum window. The measurements made while the torus vessel pressure was gradually increasing reveal that the effect is negligible as expected for the situation in which the axial stress is dominant on circular-shape vacuum windows [13,14]. The range of the vessel pressure in the test is several orders larger than that experienced by the MSE vacuum window during the plasma discharges. The change in the measured polarization angles over this pressure range is invariant within the measurement uncertainties, which enables us to neglect the correction by the vacuum-window birefringence. More detailed descriptions and experimental results on the calibration against the Faraday rotation and vacuum birefringence using the reference polarizer are to be treated in a separate publication.