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Status of PEM-based Polarimetric MSE Development at KSTAR

Jinseok Ko,* Jinil Chung, Seung Tae Oh and Won-Ha Ko
National Fusion Research Institute, Daejeon 305-806, Korea

Maarten de Bock, Henry Ong and Guido Lange
Department of Applied Physics, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands

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A multi-chord PEM (photo elastic modulator)-based polarimetric motional Stark effect (MSE) system is under development for the KSTAR tokamak. The conceptual design for the front optics was optimized to preserve not only the polarization state of the input light for the MSE measurements but also the signal intensity of the existing charge exchange spectroscopy (CES) system that will share the front optics with the MSE. The optics design incorporates how to determine the number of channels and the number of fibers for each channel. A dielectric coating will be applied on the mirror to minimize the relative reflectivity and the phase shift between the two orthogonal polarization components of the incident light. Lenses with low stress-birefringence constants will be adopted to minimize non-linear and random changes in the polarization through the lenses, which is a trade-off with the rather high Faraday rotation in the lenses because the latter effect is linear and can be relatively easily calibrated out. Intensive spectrum measurements and their comparisons with the simulated spectra are done to assist the design of the bandpass filter system that will also use tilting stages to remotely control the passband. Following the system installation in 2014, the MSE measurements are expected to be performed during the 2015 KSTAR campaign.

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I. INTRODUCTION

Many of the present-day tokamak experiments pursue advanced tokamak regimes to achieve steady-state operations. This involves optimizing the plasma shape and the profiles of its current density and pressure for stability to magnetohydrodynamic (MHD) modes by using real-time active feedback controls [1–3] and by reducing cross-field transport by changing the properties of microinstabilities [4,5].

Various reliable diagnostic, such as Thomson scattering, electron cyclotron emission (ECE), charge exchange recombination spectroscopy (CXRS), *etc.*, are available to measure the pressure profile, but the measurement of the current density profile is not straightforward. Traditionally, the motional Stark effect (MSE) diagnostic has been used to measure the magnetic pitch-angle profiles across the plasma, which, in turn, can provide the poloidal magnetic field and current density by using either magnetic reconstructions or Ampere's law. The MSE measurement utilizes the polarized light signal induced by the Lorentz electric field generated by a moving neutral in its rest frame.

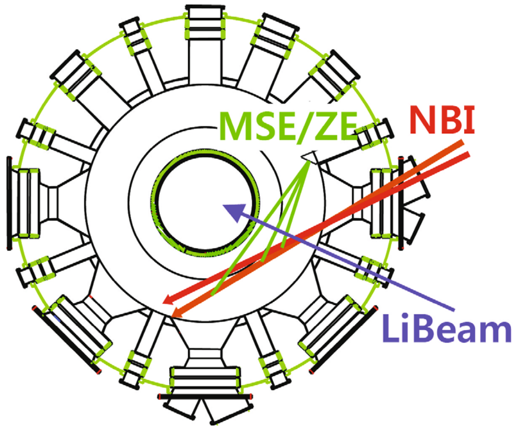

Fig. 1. (Color online) Top view of the KSTAR tokamak, the MSE lines of sight, and the NBI and Li-beam trajectories.

A multi-chord PEM (photo elastic modulator)-based polarimetric MSE system is under development for the KSTAR tokamak. The sightline view and the beam trajectories are shown in Fig. 1. In this work, the progress and the status of the MSE development for the KSTAR is presented. The spatial and the time resolutions we

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*E-mail: jinseok@nfri.re.kr

Table 1. Summary of (normalized) spatial resolutions of several tokamaks.

Machine		$\Delta r/a$ (%)		Number of	Reference
		min	max	channels	
ITER		2.5	8	20	6
JET		2	6	25	7
JT-60U		8	10	16	8
DIII-D	15T	38	23	10	9
	315T	1.5	15	16	9
	195TL	8	11	8	9
	45T, 195TU	< 1.5	8	9, 16	9
NSTX		3	5	12	10
C-Mod		10	40	10	11
MAST		5	5	35	12
KSTAR		2	8^*	$30 \sim 40$	

*R = 1.75 m

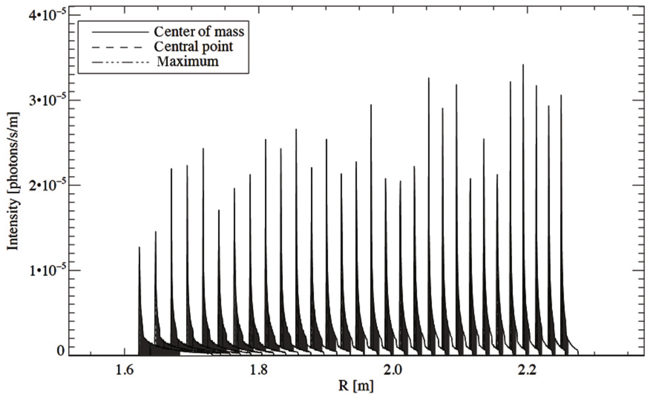

Fig. 2. Emission profiles due to the NBI (ion source 1) of the 30 lines of sight that take into account a realistic beam emission and intersection geometry (that is approximated in Fig. 1). Note the 'center of mass' of the emission and the central point of the line of sight are different because of the asymmetry in the manner of intersection. The shaded region indicates the 'width' (or parallax) of the emission profile, which is defined as 70% of the total area centered around the center of mass.

adopt are discussed in Section II. Two other main parts of the system, the front optics and the filter module, are discussed in Sections III and IV, respectively. The conclusion in Section V also includes future challenging issues such as the radial electric field.

II. SPATIAL AND TIME RESOLUTIONS

The ITER MSE requirements specify a radial resolution of $\Delta r/a \approx 5\%$ with 20 channels in order to obtain reasonable q profiles for neoclassical tearing mode (NTM) feedback (q = 1.5, 2) and reversed shear control [6]. Keeping this number in mind, Table 1 summarizes the radial resolution of the MSE system for various machines around the world. Note that the radial coverage of the MSE measurement at the KSTAR will not be uniform (denser near the pedestal region because the number of channels is doubled) and that the radial resolution will become poorer rapidly as the view passes through the magnetic axis and goes inward, as shown in Fig. 2, where the emission profiles of the MSE lines of sight across the beam are projected onto the major-radius axis. However, we would like to cover at least 10 $\sim$ 20% of the minor radius inside the magnetic axis to explicitly and directly measure the safety factor on the magnetic axis, $q0$. The typical pedestal width of KSTAR plasmas is 2 $\sim$ 4 cm, where the radial resolution would be about 2% ($\Delta r \approx 1$ cm), so a very careful channel deployment and averaging will be necessary to make a measurement in the pedestal region. Each channel would consist of 19 fibers (600 μm in core diameter, fused silica with NA = 0.22) in two columns, but under consideration is the idea that the channels at the pedestal region will only have a single column with a reduced number of fibers for precise measurements at this region.

Theoretically, the MSE time resolution is limited by the free bandwidth of the two PEM fundamental frequencies (20 kHz and 23 kHz), which is 1.5 kHz. Practically, however, it is limited by the number of photons from the beam emission. This is typically several tens of msec. The MSE systems using high-power heating beams have very high measurement speeds. The MSE of the DIII-D tokamak, for instance, is able to measure the magnetic fluctuation associated with a resistive wall mode rotated by internal coils at 20 Hz in its normal operation mode [13]. The typical H-mode energy confinement time in the KSTAR is about 100 msec, and the current relaxation time in the KSTAR $\approx 1.4a^2\kappa Te^{1.5}$ (keV)/Zeff $\approx 1.4 \times (0.5)^2 \times 1.8 \times 2^{1.5} / 2 \approx 1$ sec [14]. The real-time equilibrium reconstruction planned for KSTAR discharges can tolerate frequencies as low as 50 Hz. These three time scales seem to make 10- $\sim$ 50-msec time integration of the KSTAR MSE signals acceptable.

Foley *et al.* [15] systematically investigated the propagation of the pitch angle error in the uncertainty of the safety factor. For small pitch angle (γ), the rough scaling is $\delta q/q \sim \delta\gamma/\gamma$, which means that a 0.5° uncertainty in the MSE measurement would cause a 10% (ITER requirement) uncertainty in the safety factor near the magnetic axis (or anywhere with q_{min}). This implies that both statistical and systematic uncertainties in the MSE measurement should be kept to less than a few tenths of a degree. The time integration will need to be adjusted (increased) accordingly, and systematic errors such as Faraday rotation, vacuum window birefringence, *etc.* will be corrected via calibrations using in-vessel polarizers in front of the vacuum window. This can be done on a daily basis during the tokamak operation campaign.

III. DESIGN OF THE FRONT OPTICS

There are several challenging issues in designing the front optics that collect the light after the vacuum window at the midplane M-port of the KSTAR tokamak. The most difficult one is the sharing of the collection optics with another diagnostic system, charge exchange spectroscopy (CES). The CES utilizes the Doppler-shifted carbon-line emissions around 529 nm to measure the temperature (Doppler broadening), velocity (Doppler shift), and density (the amount of emission) of the carbon impurity in the plasma. This diagnostic has occupied the midplane M-port for several years, producing good data. Adding the photoelastic modulator and a polarizer attenuates the input. To avoid the degradation of the CES signal strength, we use a dichroic beam splitter that transmits light below 600 nm for CES and reflects light above 600 nm for MSE.

The polarization properties of polarized light, when reflected, can change. The P- and the S-polarization components with respect to the plane of incidence have their own phases and reflectivities, and their responses to the reflection are different from each other. Therefore, minimizing the relative phase shift and reflectivity between the P- and the S-polarizations at the wavelength of interest ($\sim$ 650 nm) and the angles of incidence (35 $-$ 45°) is critical. For this purpose, dielectric coatings will be applied to the dichroic beam splitter and another mirror that is already included in the optical train. Any finite differences in the phase shift and reflectivity would cause a depolarization of the signal, so the polarization response to the beam splitter and the mirror will have to be calibrated in situ via polarized-light calibrations [16].

The current layout of the optics has a significant toroidal component in its surface normal vectors (about 50%). This means the MSE polarized signals can experience a very strong Faraday rotation inside the optics media. There are glass materials (called SFL6 and S-TIH6) in which the Faraday rotation does not have a strong effect (weaker by almost two orders of magnitude than normal BK7 glass). The lenses can be fabricated out of this material. However, due to its large thermal expansion coefficient, the SFL6 material is very hard to use for vacuum windows (metal sealing). DIII-D, for example, relies on a "Bt-into-vacuum" calibration with static polarization sources in the vessel to calibrate out the Faraday effect and the stress-induced birefringence in the vacuum windows. JT60-U uses beam-into-gas calibrations. In addition to the Faraday effect on the vacuum window, the quartz silica glasses inside the PEM are also subject to this effect. Obviously, these glasses cannot be replaced with other materials. Typically, the PEM's are located far from the torus, and the normal vector is in the radial direction, usually experiencing weak radial magnetic fields outside the torus. Because of the PEM direction and location in the current KSTAR MSE design, the Faraday effect can be significant. Devising a reliable calibration method is necessary.

C-Mod recently reported that the temperature gradient across the vacuum window and the PEM was well correlated with the change in the measured pitch angle. This is presumably due to the thermal-stress-induced birefringence in the optical elements. JT60-U points out that, during the calibrations, they had to heat the mirror to the same temperature as that during the plasma operation in order to get the correct calibration factors [8]. On the other hand, no temperature effect was found for the mirrors on the C-Mod MSE [17]. Unfortunately, low-Verdet-constant glass materials (SFL6 and S-TIH6) have unacceptably high thermal birefringent coefficients. There are some other glass materials, such as NSSK5 and NSF15 (1.9×10^{-6} mm^2/N and 1.83×10^{-6} mm^2/N at 589.3 nm, respectively), that have low thermal birefringent coefficients. Therefore, a trade-off exists between Faraday rotation and thermal birefringence. Thermal effects are random and hard to analyze whereas the Faraday effect is relatively constant and systematic, depending on the toroidal magnetic field. Therefore, we are going to adopt low-thermal-birefringent materials.

IV. DESIGN OF THE FILTER MODULES

Selecting a particular region of the MSE spectrum is critical in the MSE measurement. A careful choice of the bandpass is particularly important because there are overlaps of MSE multiplets from the multiple ion sources used for the neutral beam injection. Intensive spectrum measurements done for the KSTAR tokamak also indicate that the overlap can ruin the MSE polarimetry without careful selection of the spectral region and careful beam operations [18]. Along with the measurements, the simulation of the MSE emission spectra has also been studied to determine the central wavelengths of the bandpass filters [19]. Although the components (perpendicular to the Stark electric field) are stronger in intensity than the components (parallel to the Stark field), the most red-shifted components will be measured by using the bandpass filter because these are the only components that escape from the overlap of multiple MSE spectra. Tuning of the central wavelengths by changing the angles of incidence (tilting) will be adopted such that the range of tuning will cover most plasma operations in the KSTAR (Ip = 0.5 $-$ 1.0 MA, Bt = 1.5 $-$ 3.5 T, and deuterium beam energy of 70 $-$ 100 keV).

The effect of tilting an interference filter to change the central wavelength of the transmission function has been studied. A comparison between the filter specifications from the manufacturer and the measurements of the filter properties has been made [20]. The measured value of the central wavelength as a function of the tilt angle of the filter (up to ± 25°) corresponds well to the designed one. A maximum difference of 0.2 nm was obtained between the experimental position of the central

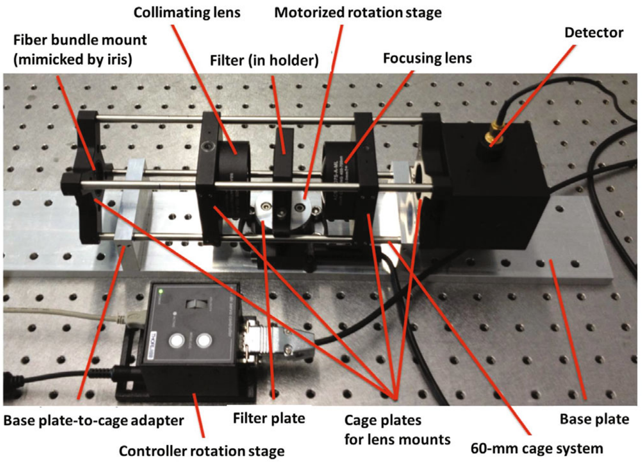

Fig. 3. (Color online) Overview of the KSTAR MSE sensor module prototype.

wavelength and the designed expectation, which corresponds to a relative error of 7.5% and is acceptable for central wavelength tuning. The central wavelength also has almost no dependence on the divergence of the incident beam.

The full width at half maximum (FWHM) and the transmission peak agree well with the expected values for inclination angles of the filter up to approximately 3°. For larger angles, the design predicts higher values than the measured FWHM, and the reverse trend holds for the peak transmission. Possible explanations for this difference include the temperature effect.

A standard client tool is available to control the motor angle by using the engine controller, and this tool is provided by the manufacturer of the motorized rotation stages (CR1/M-Z7E & TCH002 from Thorlabs, Inc.). However, custom software is under development to tune the filter by using the available ActiveX component. With the new customized control, it is possible to tune the filter according to its central wavelength and not to its angle, which is necessary for the MSE diagnostic. The accuracy obtained is on the order of 0.5% and is compatible with the MSE requirement. The software also allows sequences creation, which consists of executing a series of a predefined central wavelength and a corresponding time delay. One PC can control 5 controller hubs, each of which can accommodate up to 6 rotational stage/controller sets, resulting in a maximum of 30 sets. Fig. 3 shows the prototype of the filter and its controller.

V. CONCLUSION

The MSE diagnostic system is under development with an aim to commissioning in the 2015 KSTAR experimental campaign. The front optics and the filter module are already in the process of being procured, and the other parts, such as the APD detectors and digitizers, will be selected and ordered soon. The most challenging issues in the design include the fact the collection optics have to be shared with the existing CES diagnostic system. A dichroic beam splitter will be used to separate signals with different wavelengths.

Angle-tuning interference filters will be used to change the pass band of the signals and to collect the correct polarization components. Customized control software will enable the precise remote control based on the practical operation parameter - the central wavelength.

There are still some difficult issues to be resolved. The intrinsic radial electric field, Er, will be a critical limit in the MSE measurements. Every tokamak has a means to correct or an ‘excuse’ for not correcting it. DIII-D is a good example to work very hard with this problem. For them, this is the reason that they installed an additional MSE system to look at the same spatial location. Unfortunately, the spatial resolutions were so poor that it was not very useful. Instead, they rely on direct Er measurements from toroidal and poloidal CXRS systems. JET [21] and NSTX [10] also use the CXRS measurements. JT-60U uses two MSE systems looking at two (co- and counter) NBI’s to correct the Er. Neither method will be available in KSTAR in the near future. In DIII-D, a rule-of-thumb is that $\sim$ 10 kV/m gives a pitch angle change of 0.1°. In C-Mod cases, this can happen with much lower Er ($\sim$ 5 kV/m at the edge channel) [22]. During some ELM-free H-modes in C-Mod plasmas, Er could be as high as 300 kV/m [23]. Therefore, in general, we expect a non-negligible effect from the Er in the MSE measurements, especially, in the pedestal region. In KSTAR, a new lithium diagnostic beam system was successfully commissioned during the 2013 campaign, and the Zeeman split spectra were measured and exhibited a distinguishable feature of the Zeeman polarization components. A similar approach can be applied to the Li resonance emission (2S-2P, 670.8 nm) to infer the pitch angle near the pedestal region without concern for the perturbation from the local electric fields [24].

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