Real-time MSE measurements for current profile control on KSTAR\textsuperscript{a)}

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To step up from current day fusion experiments to power producing fusion reactors, it is necessary to control long pulse, burning plasmas. Stability and confinement properties of tokamak fusion reactors are determined by the current or \( q \) profile. In order to control the \( q \) profile, it is necessary to measure it in real-time. A real-time motional Stark effect diagnostic is being developed at Korean Superconducting Tokamak for Advanced Research for this purpose. This paper focuses on 3 topics important for real-time measurements: minimize the use of \textit{ad hoc} parameters, minimize external influences and a robust and fast analysis algorithm. Specifically, we have looked into extracting the retardance of the photo-elastic modulators from the signal itself, minimizing the influence of overlapping beam spectra by optimizing the optical filter design and a multi-channel, multiharmonic phase locking algorithm.

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I. INTRODUCTION

With superconducting magnetic coils, a flexible double-null configuration, and multiple heating systems, the Korean Superconducting Tokamak for Advanced Research (KSTAR) is well equipped for investigating high performance, long pulse scenarios\textsuperscript{1} (Figure 1 shows a top view of the KSTAR tokamak together with its main parameters). One of the prerequisites of these advanced scenarios is control over the current or \( q \) profile. This in turn requires a real-time equilibrium reconstruction constrained by accurate measurements. In particular, local magnetic field measurements in the plasma core are essential. Motional Stark effect (MSE) is a well-established technique of obtaining those central magnetic measurements.

MSE is based on the analysis of light emitted by a neutral beam injected into the plasma. KSTAR will use ion source 1 of the heating neutral beam NBI-1 for MSE (see Figure 1). Although several techniques for retrieving magnetic field information from the beam emission exist,\textsuperscript{2} the most established technique is that of photo-elastic modulator (PEM)-based polarization measurements.\textsuperscript{3} Hereby, 2 PEMs, driven at different frequencies, encode the polarization information of the beam emission into an intensity modulation. The polarization angle \( \gamma \) can then be retrieved by taking amplitude ratio of the measured second harmonic signals \( I_{2\omega_0} \) of the 2 PEMs:

\[
\tan(2\gamma) = \frac{J_2(R_2)I_{2\omega_0}}{J_2(R_1)I_{2\omega_0}},
\]

where \( J_2 \) is the second order Bessel function of the first kind, \( R_1 \) and \( R_2 \) are the (amplitudes of the modulated) retardances or phase shifts induced by PEM 1 and 2, respectively, and \( \omega_1 \) and \( \omega_2 \) are the frequencies at which PEMs are driven.

The relation between the thus obtained polarization angle \( \gamma \) and the magnetic field is given by:

\[
\tan(\gamma) = \frac{A_0 B_Z + A_1 B_R + A_2 B_\phi}{A_3 B_Z + A_4 B_R + A 5 B_\phi},
\]

where the \( A \)-coefficients depend on geometry and (weakly) on the radial electric field of the plasma. The polarization angle \( \gamma \) is wavelength dependent: the outer 6 emission lines, \( \pi \pm 2, \pi \pm 3, \) and \( \pi \pm 4, \) will have a polarization angle exactly 90\(^\circ\) different from the 3 central \( \sigma \) lines, \( \sigma_0 \) and \( \sigma \pm 1 \). A narrow, optical bandpass filter is used to select out either the \( \pi \) or \( \sigma \) part of the spectrum.

In real-time diagnostics, systematic deviations are even more important than in diagnostics with a post shot, off-line analysis. Sections II and III focus on 2 techniques of minimizing systematic deviations: extracting the retardance from the measured signals themselves and optimizing optical filter design. Section IV introduces a custom real-time analysis algorithm and discusses its benefits over commercially available systems.

II. RETARDANCE RETRIEVAL

Many external effects can influence the measurement of \( \gamma \): Faraday rotation in windows and lenses, P and S plane reflections on dielectric mirrors (or dielectric coatings on metallic surfaces), misalignment, reneutralized beam particles, etc. Monitoring these requires regular calibrations. However, at least 2 parameters affecting the measurement can be monitored continuously: the retardances on the 2 PEMs (see Eq. (1)). This allows to verify the retardances set by the PEM controllers, but more importantly it means the measured retardances can be taken directly into account in the real-time analysis. The relation between the PEM retardances, \( R_1 \) and \( R_2 \), and the measured harmonic amplitudes is:

\[
\frac{J_2(R_1)}{J_2(R_2)} = -\frac{I_{2\omega_2}}{I_{2\omega_1}}.
\]
FIG. 1. Top view schematic of the KSTAR tokamak indicating the positions of the MSE viewing range, neutral beam positions, and the main KSTAR parameters. The 3 dotted lines indicate outer edges and center of the viewing range, the total number of channels is planned to be of order 30.

By scanning a laser over the PEM aperture, a profile of the retardance over the aperture can be measured. This is shown in Figure 2 for a PEM set at half a wave retardance (i.e., a $\pi$ phase shift). One observes a strong, circular symmetric retardance profile where the set retardance only corresponds to the central maximum. This is compatible with a standing wave pattern over the PEM.

Because the complete available PEM aperture is used in MSE diagnostics, this retardance profile has consequences when retrieving $\gamma$ using Eq. (1). If the PEMs are placed in the aperture plane of the collection optics, Eq. (1) is generalized to

$$\tan(2\gamma) = \frac{\langle J_2(R_2) \rangle I_{2\omega_n}}{\langle J_2(R_1) \rangle I_{2\omega_2}}.$$  (4)

Equations (1) and (4) will only give the same result if $R_1$ equals $R_2$ and the retardance profile shape is the same for both PEMs. Fortunately, when using the complete aperture also Eq. (3) is generalized to

$$\frac{\langle J_2(R_x) \rangle}{\langle J_4(R_x) \rangle} = -\frac{I_{2\omega_n}}{I_{4\omega_n}}.$$  (5)

With the shape of the profile parametrized from the lab measurements shown in Figure 2, a look-up table can be formed, relating the ratio $-I_{2\omega_n}/I_{4\omega_n}$ to $\langle J_2(R_x) \rangle$. This way all necessary information to retrieve $\gamma$ can be obtained from the actual signal itself, without having to rely on the external settings. This improves the robustness of the (real-time) MSE measurement.

III. SPECTRAL SIMULATION AND SYSTEM OPTIMIZATION

In the ideal situation of a pencil-like beam and line-of-sight, the $\pi$ and $\sigma$ lines of the MSE spectrum will be well separated and the corresponding $\gamma$ will differ by exactly 90°. For a realistic beam width and velocity distribution and a finite optical collection angle, the spectral lines will broaden causing $\pi$ and $\sigma$ lines to overlap. Moreover, the 3 ion sources for NBI-1 and the 3 energy components of each lead to a final complex MSE spectrum. Figure 3 shows a simulation of the MSE spectrum for each ion source separately (red, blue, and green lines) and the final total spectrum (black line). Apart from the intensity, the spectral overlap also affects the wavelength dependence of $\gamma$, resulting in a deviation from the simple formula of (2). The wavelength range selected by the optical filter should be such that this deviation is minimal. For KSTAR, best results are obtained by selecting that part of the spectrum where only emission of ion source 1 is present. This corresponds with the long wavelength limit of the total spectrum (“red $\pi$”) under the condition that ion source 1 is at full energy (95 keV) and ion source 2 is limited below 90 keV (see Figure 3). Ion source 3 can go up to the full energy.

Apart from the intensity, the spectral overlap also affects the wavelength position also the shape and the bandwidth of the filter influences the final measurement. Interference filters, as intended for the KSTAR MSE system, can have multiple cavities steepening the edges of the filter, while the width can go down to 1 Å. A wider filter smooths $\gamma(\lambda)$, but when too wide spectral overlap will occur. Steeper edges allow for wider filters before suffering from spectral overlap but do cause the spectral overlap to be more sudden when it occurs. For KSTAR, simulations with numerous filters favored a 2 cavity filter with a full width half maximum of 4 Å (2C4). As can be seen in Figure 4, the 2C4 filter has
FIG. 4. The effect of different filter designs (xCy stands for x cavity filter with y Å width) on the deviation of the measured $\gamma$ from the ideal $\gamma$ as function of the ion source 2 voltage (ion source 1 and 3 both at the maximum of 95 kV).

a constant and low residual up to an ion source 2 energy of 90 keV.

IV. REAL-TIME ALGORITHM

To derive the retardance and $\gamma$ from the measured signal, it is necessary to extract the harmonic amplitudes. This can be done using commercially available phase-locked-loop (PLL) systems. However, several arguments call for a custom solution.

First, the phase difference between the PEM reference signals and the different MSE channels is the same for all channels. Therefore, using the information of all channels simultaneously results in lower noise. Moreover, all 4 harmonics can be used simultaneously as well, again reducing noise levels. Figure 5 shows the real and imaginary parts of the harmonics and the derived phase. Figure 6 shows that 10 ms after beam switch on the real-time algorithm has determined the phase to within 0.5° on a 1 MHz sample signal analyzed at 1 kHz. The data shown in Figures 5 and 6 are based on measured data from the MAST MSE diagnostic.

Second, the determination of $\gamma$ needs “signed” amplitudes. If not (4) would only be able to return $\gamma$ between 0 and $\pi/2$, whereas $\gamma$ does change sign when crossing the magnetic axis. Such signed amplitudes are obtained by “rotating” the complex harmonics over their phase to the real axis (see Figure 5). An extra benefit is the separation of noise (along the imaginary axis) from real fluctuations (along the real axis), providing a real-time error estimate.

Finally, a custom algorithm can readily include the determination of the PEM retardances as described in Sec. II, as well as perform further real-time operations to return apart from $\gamma$ also a real-time values of the position of the magnetic axis and $q_0$. When combined with real-time optical boundary reconstruction, even a real-time $q$ profile could be returned without the need for full equilibrium reconstruction.

V. SUMMARY AND OUTLOOK

Real-time MSE is an essential diagnostic for advanced control over the $q$-profile in tokamaks. For real-time diagnostics, it is important to minimize the use of ad hoc parameters, minimize external influences on the signal and a robust and fast analysis algorithm. The first is achieved a.o. by retrieving the PEM retardances from the signal itself. Regarding the second point extensive simulations showed that for optimal KSTAR MSE measurements the “red” end of the beam spectrum should be selected by a 2 cavity 4 Å wide interference filter, while running ion source 1 of NBI-1 at the full energy of 95 keV and keeping ion source 2 below 90 keV. With respect to the third point, a custom real-time analysis algorithm is favored over commercially available PLLs, because of lower noise levels when combining data from multiple MSE channels and multiple harmonics.

The above design considerations and results will be taken into account in the further development of the KSTAR MSE system and analysis software.

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