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Instrumentation for a multichord motional Stark effect diagnostic in KSTAR^{a)}

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The motional Stark effect (MSE) diagnostic is used to measure the radial magnetic pitch angle profile in neutral beam heated plasmas. This information is used to calculate the safety factor, q , with magnetic equilibrium reconstruction codes such as EFIT. The MSE diagnostic is important during active shaping of the q profile to optimize confinement and stability, and it has become a key diagnostic in high performance tokamaks. A multichord photo-elastic modulator (PEM) based MSE system is being developed for a real-time plasma current profile control in Korea Superconducting Tokamak Advanced Research (KSTAR). The PEM-based approach is a standard method that measures the polarization direction of a single Stark line with narrow tunable bandpass filters. A tangential view of the heating beam provides good spatial resolution of 1–3 cm, which provides an opportunity to install 25 spatial channels spanning the major radius from 1.74 m to 2.84 m. Application of real-time control is a long-term technical goal after commissioning the diagnostic in KSTAR, which is expected in 2015. In this paper, we describe the design of this newly-constructed multichord MSE diagnostic in KSTAR. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4891161>]

I. INTRODUCTION

In the 1990s, it was discovered that modifications to the relaxed Ohmic current profile could yield significant improvements in energy confinement. This has motivated considerable research into Advanced Tokamak plasma regimes, where the current profile is actively controlled to optimize plasma performance. Real-time active control of the current profile requires real-time measurement of the current profile.

Real-time control of the current profile in long-pulse, AT plasmas is a major component of the KSTAR research program. Other tokamaks, such as JET, ASDEX-U, DIII-D, JT-60, and MAST, have used motional Stark effect (MSE) to measure the current profile.^{2–5} We propose also to measure the magnetic field pitch-angle profile with a MSE diagnostic in KSTAR that is described in this paper. This profile will be used, in conjunction with magnetic pickup loops at the plasma periphery in equilibrium-reconstruction codes such as EFIT (Equilibrium Fitting) to compute the radial profile of toroidal current and the plasma equilibrium.¹ A PEM based multichord MSE system is currently being developed in KSTAR for real-time plasma current profile control, and will be commissioned during 2015 and 2016 campaigns. The system observes the Stark splitting of a D-alpha line at 656.1 nm by the electric field associated with neutral deuterium atoms injected from the first neutral heating beam system labeled NBI-1. Figure 1 shows the location of a cassette of the beam diagnostic and the neutral beam. KSTAR has a maximum toroidal field of 3.5 T at major radius of 1.8 m, a minor radius of

0.5 m, and operational plasma current of up to 1 MA (2013 campaign). Directions of both the toroidal field and the plasma current are clockwise. The NBI-1, which lies in the horizontal midplane, consists of three positive ion sources, and was designed for generating a beam with a divergence angle less than 1°. The cross-sectional shape of each beam is a vertically elongated rectangle (0.2 m × 0.6 m). The first ion source launched in 2010 delivered a beam power of 1.5 MW at a beam energy of 95 keV.⁶ The second and third ion sources became available during the 2013 and 2014 campaigns, respectively, with a power of 2.0 MW at 95 keV beam energy.

FIG. 1. Top view of the KSTAR tokamak showing locations of a set of neutral beam from the NBI-1 on port L and observation lines of MSE diagnostic in the beam diagnostic cassette on port M.

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II. DESIGN CONSTRAINTS AND LIMITATIONS

Several critical restrictions were considered in the design of the KSTAR MSE system. Specific concerns were: observing a heating beam that consists of three distinct ion sources; and sharing a vacuum window with a charge exchange-recombination spectroscopy (CES) diagnostic in a narrow viewport cassette.

Regarding the neutral heating beam, the injecting angle of the second and the third beams is 4° relative to the center of the first (middle) beam. This is problematic for the MSE measurement because the spectrum of the Stark splitting is much more complicated and the beam width is broader when all three beams are injected simultaneously. Although modulating the beam is a solution for a reference measurement, this cannot be routinely used because the beam is a major heating source in KSTAR. However, adjusting the energy of each beam (in the range of 80–95 keV) can result in an isolated line at the edge of the total Stark spectrum due to the Doppler shift. This solution has been adopted and will allow the heating beam to be used without modulation, and it is realized by careful design of narrow scanning bandpass filters for each channel with appropriate beam energy combinations.

Another limitation of the system was that the narrow width of tokamak viewport could not contain a commercialized dual PEM normal to the toroidal magnetic field after having its cassette system. To solve this problem, a 2-m-long cassette system for the beam diagnostic has been designed and installed with an optimized tangential view of the tokamak on the median port M with the NBI-1. The PEM has been introduced next to the vacuum window to make it fit in the cassette. The optical axis of the system passes through the center of the vacuum window and the PEM as shown in Figure 2. The tangential view is advantageous in that no in-vessel optical array is required, but the diagonal arrangement of optical components including a vacuum window, PEMs, and lenses are more affected by the Faraday rotation.

FIG. 2. Three-dimensional modeling of the 2-m-long beam diagnostic cassette system on port M. View “A” shows the front-end optical system of the MSE sitting in a narrow interior of the cassette. B: a dual PEM, C: enclosure of collection optics, D: mounting socket of the MSE fiber bundle, E: mounting socket of the CES fiber array, F: vacuum window for a coherence imaging, G: vacuum system, and H: in-vacuum shutter system that protects the vacuum windows.

Concerning constraints on sharing the vacuum window in a narrow cassette, the cassette has three viewport windows arranged vertically. It was designed to contain a coherence imaging diagnostic on the top, MSE and CES in the middle (midplane), and beam emission spectroscopy (BES) on the bottom window. Since there was no escape from sharing the midplane window due to limited space, satisfying both diagnostics with a common collection optic system was one of the biggest challenges of developing the system. The narrow width of cassette also allowed a 6-in. Conflat vacuum window in the midplane. The size of the collection lenses, which is basis for collecting light from the focal plane along the beam path, was limited by the size of the window and the space of cassette interior.

III. DESIGN OVERVIEW OF THE MSE SYSTEM

Figure 3 shows an overview of the MSE system design. Collection optics relay the beam emission through two crossed photo-elastic modulators. The dual PEM, which mounts two crossed PEMs in a single enclosure, is a key optical component in the polarization measurement. Optical retardation axes of the two PEMs are at 45° with respect to each other, with one operating at 20 kHz and the other at 23 kHz. The ratio of the detector signal at twice the modulating frequencies is directly related to the magnetic pitch angle. The housing of the dual PEM for the KSTAR MSE is made of a plastic material, which is non-magnetic and non-conductive, to survive in a high superconducting TF magnetic field that stays on all the time during the experiment. Since it must share a vacuum window with the CES on the midplane in the cassette, a collection optic system is being fabricated for both diagnostics using a dichroic beam splitter that splits the incoming light into two wavelength ranges. This avoids attenuating the light intensity for the CES by the MSE linear polarizer. Optical components in the optical system influence the original polarization direction by means of Faraday rotation, Fresnel effects, and additive systematic errors. All those effect need to be calibrated from the raw measurement.

The MSE fiber bundle is connected vertically with a linear polarizer to the optic system enclosure, while the CES fiber array is connected horizontally as shown in Figure 2. The 25-channels MSE fiber bundle comprise 475 fibers each 35 long. Fibers have a $600\ \mu\text{m}$ silica core, and 19 cores are grouped vertically to the collection optic end and circularly to the detector end with a diameter of 3.3 mm as shown in Figure 3 A. This stays within the 3.5 mm diameter limit at the detector end.

A redshifted π component is isolated using scanning multi-cavity narrowband filters mounted in the detection system. The multi-cavity provides a more nearly rectangular transmission curve, and it will be a great advantage for more reliable measurements in a complicated spectrum. The system allows the filters to be tilted dynamically, thereby allowing for rapid tuning of the center wavelength during a single discharge. A 2.0 nm of tuning range of the center wavelength is suggested for KSTAR operational parameters of beam voltages (70–100 keV) and toroidal magnetic field strengths (1.5–3.5 T).⁷ APD (avalanche photodiode) modules with high-

FIG. 3. Overview of the PEM based multichord MSE system in KSTAR. The MSE and the CES share their collection optics using a dichroic beam splitter. Fiber bundle layout of a single channel is indicated in A.

speed amplifiers (300 kHz) will be equipped as detectors, and the grating survey spectrometer is used for the system calibration. A maximum 10^9 photons/s is expected to arrive at the detector, and this high optical throughput may allow a time resolution of a few tens of milliseconds. The 25 viewing lines with large array of fibers covering the major radius from 1.74 m to 2.28 m provide good spatial resolution as shown in Figure 4.

IV. INTEGRATION OF THE SYSTEM

The KSTAR MSE system will be used for a real-time current profile control. A special digital signal processing (DSP) firmware allows a digitizer to function as a digital lock-in amplifier. Fifty four data acquisition channels with a maximum sampling rate of >1 MHz will be used. Twenty five channels are for a real-time DSP, 4 channels are for reference signals from the PEMs, and the last 25 channels are used as a second shadow digitizer that records the raw full rate data for verification and possible additional post-shot lock-in processing. While the PEM based technique is conventional, its application to a real-time control is a challenge area for a steady-state operation in tokamaks. Application of real-time control is a long-term physical and technical goal after commission-

ing. Offline post processing with raw signals on the second shadow digitizer and real-time communication with the rtEFIT (real-time EFIT) using signals from analog lock-ins will be tried prior to applications of the DSP techniques. A method to prove low and high DC signals to the rtEFIT for a detection of invalid MSE data is being investigated.

V. SUMMARY

A 25 chord MSE is being developed to provide coverage on the plasma low field side along the NBI-1 deuterium heating beam. The spectral overlap of each of the three ion sources in NBI-1 yields a complex Stark spectrum. Space available for optical components in the beam diagnostic cassette is very limited. However, final design of the system has been completed with favorable specifications. The tangential view provides a good spatial resolution of 1–3 cm for covering the major radius from 1.74 m to 2.28 m, and the time resolution expected faster than a few tens of ms. All the sub-systems are being fabricated and they will be assembled all together in the tokamak and a diagnostic room before the 2015 campaign expected in the middle of the year.

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FIG. 4. Computed spatial resolution of the MSE system. Spatial resolution in between the plasma core and the edge is expected 1–3 cm.

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