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Design and fabrication of a multi-purpose soft x-ray array diagnostic system for KSTAR[a)]

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A multi-purpose soft x-ray array diagnostic system was developed for measuring two-dimensional x-ray emissivity profile, electron temperature, Ar impurity transport, and total radiation power. A remotely controlled filter wheel was designed with three different choices of filters. The electron temperature profile can be determined from the ratio of two channels having different thickness of Be layer, and the Ar impurity concentration transport can be determined from a pair of Ar Ross filters (CaF_2 and NaCl thin films). Without any filters, this diagnostic system can also be used as a bolometer. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4734035]

I. INTRODUCTION

Studies of fast and transient phenomena have become more important in tokamak plasmas in relation to MHD activities,[1] sawtooth crash, ELM bursts,[2] impurity transport,[3,4] and turbulence during H-mode operations. It is important to measure soft x-ray emission with high spatial and temporal resolutions; such measurements can provide abundant information on plasmas such as precursor of sawtooth,[5] resistive wall mode behavior,[6] trace-impurity injection for particle-transport analysis,[7] and so on. For the detection, silicon photodiode is widely used because of its good quantum efficiency, fast time response, compact size, low-cost, and easy-handling features.

The soft x-ray radiation emitted from tokamak plasma is determined by its physical parameters and is closely related to the charge states and processes of the main ion impurities. The electron temperature in the core region reaches a few keV, so that x-ray bremsstrahlung is abundant from collisions between electrons and ions. In addition, characteristic line radiation from the impurity ions significantly enriches the spectrum. In the KSTAR experiment, C VI lines of 0.3–0.5 keV and helium-like and hydrogen-like Ar lines of 2.8–4.0 keV are the main impurity lines due to the carbon plasma facing component and Ar gas puffing.[8] According to the calculation results of the multi-ionized species transport code[9] and the Hebrew University Lawrence Livermore Atomic Code (HULLAC),[10] the dominant radiation of the soft x-ray band from the KSTAR plasma is bremsstrahlung.[11] The approximate ratio of the line radiation power to the bremsstrahlung power is only 0.01. Moreover, the C lines are negligible with metallic foil filters since its cut-off energy is higher than several hundred eV. Therefore, the total soft x-ray power arriving at the detector can be regarded as having a continuum spectrum.

In this work, the soft x-ray array diagnostics has been designed, fabricated, and installed on the KSTAR. Due to the similarity between the multi-energy method and Ar Ross filter spectroscopy, the diagnostic module was designed for multi-purpose use with a rotating filter wheel selecting a specific filter.

II. EXPERIMENTAL SETUP

The soft x-ray array diagnostic is installed inside the KSTAR vacuum vessel mounted on a 6-in. conflat flange, as shown in Fig. 1. Each array system consists of two photodiode array detectors (AXUV-16ELG), two apertures, a filter wheel, a number of pins of electrical feed-through, and a rotary drive to adjust the filter wheel outside the vacuum vessel. The filter type, which can be a pair of beryllium foils, a pair of Ar Ross filters, or a blank opening, and the shutting of the aperture can be selected by the rotary motion manipulator. The ball spring plunger inside the rotary drive helps to position the filter wheel precisely when it is rotating. A pair of silicon photodiode array detectors is placed right next to each other to view the same plasma volume. The active area of each detector element is $5 \times 2\ mm^2$ and the aperture size is $5 \times 1\ mm^2$. The distance between the detector pair (3 cm) is much smaller than the toroidal spatial resolution (~20 cm), so that the two detectors are considered to have the same line of sight. Each array has 16 channels with a viewing angle of 45°, providing a spatial resolution of 5 cm in poloidal cross section. Two diagnostic modules are installed in the same poloidal plane with exactly symmetric positions with respect to the midplane, as depicted in Fig. 2. Injection of Ar as the diagnostic trace gas

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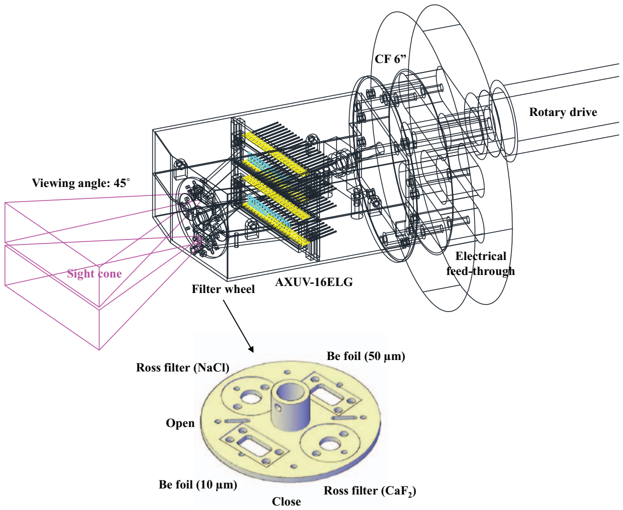

FIG. 1. Schematic of the soft x-ray array diagnostics for KSTAR (top) and the structure of the filter wheel (bottom).

is provided by a piezo-valve on the midplane in the KSTAR vacuum vessel.

A. Beryllium filter

In order to filter out photons having energy lower than the soft x-ray band, a metallic foil is utilized. The metallic foil should not have any resonance lines in the soft x-ray band. Beryllium is satisfactory to meet these conditions. According to the x-ray continuum radiation from hot Maxwellian plasmas, the radiation spectrum is a function of electron density n_e, effective atomic number Z_{eff}, and electron temperature T_e. Since the continuum radiation power depends linearly on n_e and Z_{eff}, these parameters disappear in the ratio of the signals through a thin foil to a thick foil, so that the ratio depends only on T_e being inside the exponential function. Therefore, it is possible to evaluate T_e with multi-energy measurements using multi-filters.[12] The energy spectrum arriving at the detector is proportional to the exponential term of the continuum

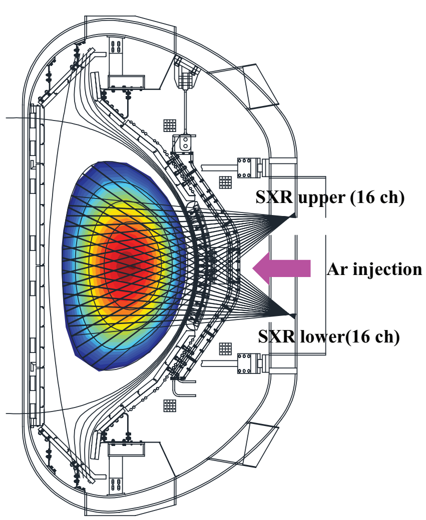

FIG. 2. Line of sight of each detector element and the position of the Ar injector on midplane.

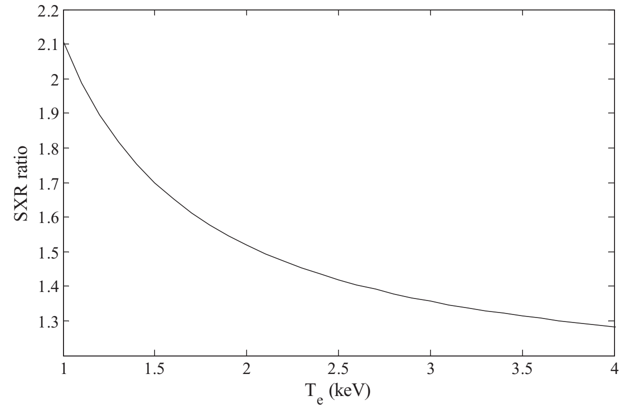

FIG. 3. Soft x-ray signal ratio as a function of T_e. Be filters of 10 μm and 50 μm are assumed.

radiation and the transparency of the filter T_f, which is a function of the incident photon energy E, as shown in Eq. (1):

$$S_{ar}(E) \propto \exp\left(-\frac{E}{kT_e}\right) T_f(E). \tag{1}$$

The detection efficiency is approximately given by $\varepsilon_D = 1 - T_{Si}(E)$, where $T_{Si}(E)$ is the transparency of the Si detector.[13] The photo-current I_{ph}, induced by incident photons, is derived by

$$I_{ph} \propto \int_0^\infty \exp\left(-\frac{E}{kT_e}\right) T_f(E)\,[1 - T_{Si}(E)]\,dE. \tag{2}$$

In this experiment, Be filters of 10 μm and 50 μm were adopted, of which the cutoff energies are 0.5 and 1 keV, respectively. By calculating the integral in Eq. (2), a plot of the signal ratio as a function of T_e is obtained [Fig. 3]. The fluctuation of T_e and the soft x-ray pressure $n_Z T_e$ can be observed with high temporal resolution using this method.[14]

B. Ar Ross filter spectroscopy

With the same detector setup described above, impurity detection was also attempted using Ross filters. The basic concept is to use different elements or compounds with adjacent or nearly adjacent atomic numbers.[15,16] To investigate the Ar impurity transport, CaF_2 and NaCl materials are used

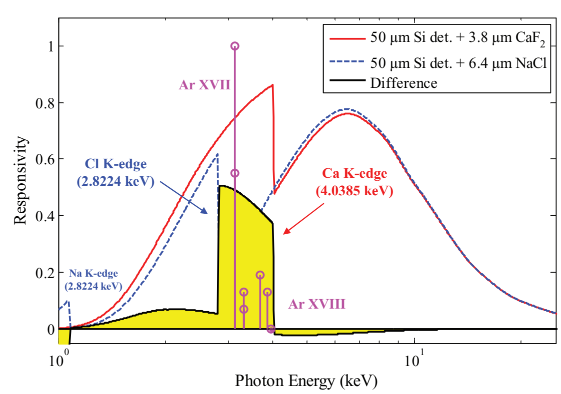

FIG. 4. Responsivity of the 50 μm Si detector with a pair of Ross filters. The difference between the two spectra can be used as a bandpass filter.

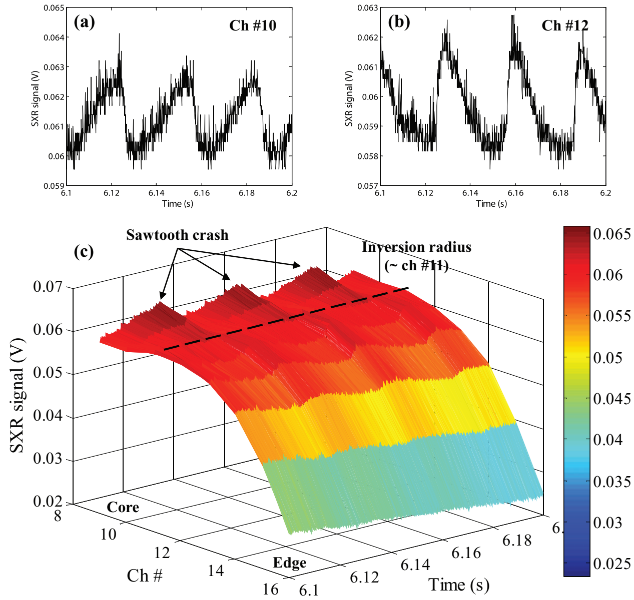

FIG. 5. Soft x-ray signals of (a) channel 10 and (b) channel 12 during sawtooth oscillation (Shot 6306). (c) Time evolution of the soft x-ray signals from core to edge channels. Inversion radius lies on channel 11 (15 cm of radius) and the sawtooth period is 30 ms.

for bandpass filtering between the Cl K-edge (2.8224 keV) and the Ca K-edge (4.0385 keV).[17] The thickness of the two filter materials should be decided based on the transparency curve. Figure 4 depicts the responsivity of the Si detector with 50 μm thickness combined with each Ross filter. The area, except for the passband region, can be minimized with CaF_2 and NaCl films of 3.8 μm and 6.4 μm thickness, respectively.[18] Dominant Ar XVII lines and Ar XVIII lines exist in the energy passband. This method can provide information on Ar impurity transport with high temporal resolution up to 10 μs; therefore, the transient or fast diffusion of Ar impurities can be studied. This method has already been applied to DIII-D and has produced results from the preliminary tests.[19,20]

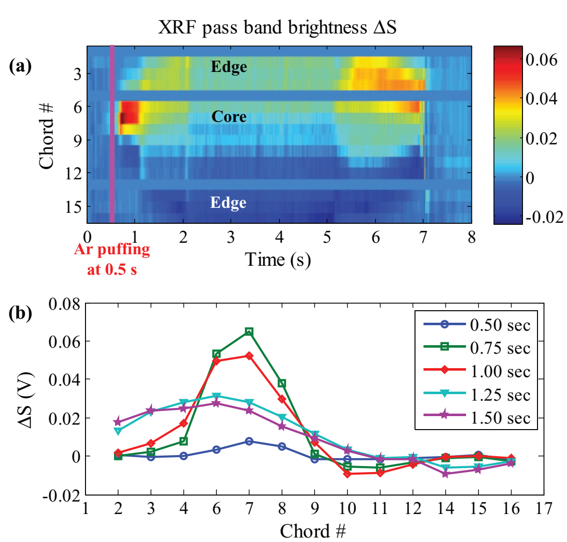

FIG. 6. (a) Time evolution of the signal difference (Shot 6371). (b) Ar diffusion is seen after Ar puffing at 0.5 s. Bad channels 1, 5, and 13 are attributed to malfunctioning in the pre-amplifier electronics.

III. PRELIMINARY RESULTS

Figure 5 shows sawtooth oscillations with periods of 30 ms; these were observed by Be filtered soft x-ray signals, where a high emission intensity bursts are seen. From the shape of the sawteeth in channels 10 and 12, the inversion radius is at 15 cm near channel 11. Argon impurity lines were also obtained by rotating the filter wheel by 90° in order to select the Ar Ross filters; the preliminary results are presented in Fig. 6. Argon gas puffing took place at 0.5 s along the midplane, and it is seen that the core channels detect the helium-like Ar impurity. It seems to take about 0.5 s for Ar to reach the core region.

IV. SUMMARY

Soft x-ray diagnostics based on Si photodiode array detectors has been designed, fabricated, and installed on KSTAR. Beryllium filters and Ar Ross filters were installed on a filter wheel that could be externally controlled. As the preliminary results from the 2011 KSTAR campaign, sawtooth oscillations, and Ar impurity diffusion were observed by the selected Be filters and Ar Ross filters, respectively. For the 2012 campaign, a total of 256 channels are under preparation for tomography of the x-ray emissivity with multi-color capability.

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