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$$m_p \equiv \text{const} \frac{I(\lambda_o) \cos \theta \lambda_b}{\Delta \lambda} \propto B \cos \theta$$

since,

$$\Delta \lambda_b = Z \frac{\mu_o \lambda_o^2 B \Delta M}{2 \pi \hbar c}$$

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A three-year research program for the development of novel XUV spectroscopic diagnostics for magnetically confined fusion plasmas is proposed. The new diagnostic system will use layered synthetic microstructures (LSM) coated, flat and curved surfaces as dispersive elements in spectrometers and narrow band XUV filter arrays. In the framework of the proposed program we will develop impurity monitors for poloidal and toroidal resolved measurements on PBX-M and Alcator C-Mod, imaging XUV spectrometers for electron density and temperature fluctuation measurements in the hot plasma core in TEXT or other similar tokamaks and plasma imaging devices in soft x-ray light for impurity behavior studies during RF heating on Phaedrus T and carbon pellet ablation in Alcator C-Mod.

Recent results related to use of multilayer mirrors in XUV plasma spectroscopy are presented. We also discuss the latest results relative to q_0 and local poloidal field measurements using Zeeman polarimetry.

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I. Introduction

Our plasma spectroscopy laboratory began a research program in magnetically confined fusion plasma diagnostics in 1976. From the beginning the emphasis has been on adapting and implementing new advances in optical and detector technology for practical diagnostic instrumentation. For instance, this laboratory pioneered the use of microchannel plate image intensifiers in XUV spectroscopy and showed that these devices could be used in a tokamak environment with low and moderate levels of neutron and γ -ray yields. By using these detectors, which simultaneously measure a large number of spectral and/or spatial elements, impurity concentration and power loss estimates in ohmically and auxiliary heated tokamaks can be performed on a routine basis. Thus, for instance, a grazing incidence spectrograph equipped with such a detector has been used to study the impurity behavior during ICRF heating on PLT, or more recently, to study local electron density and temperature variations on the TEXT tokamak¹ during ergodic magnetic limiter activation. During the last three years a poloidal field diagnostic has been developed which measures the circular polarization of near ultraviolet and visible emission from intrinsic or injected ions in the plasma. The Zeeman effect induced circular polarization is directly proportional to the magnetic field along the line of sight and was used to determine the poloidal field in the TEXT tokamak. During 1989-90 these measurements were further improved by measuring the circular polarization of the visible emissions from a Li neutral beam using narrow band pass filters, leading to new determinations of the safety factor q under a variety of conditions. In addition to applying new technologies to magnetic fusion diagnostics, the program has also emphasized installing them on major machines in order to demonstrate that they lead to improved diagnostic analysis of the plasma. This experience is then used in the development of future diagnostics. As a consequence, instruments constructed at this laboratory have been installed on a number of plasma devices including Alcator A and C, DIII-D, EBT, PLT, TEXT, TFR (France), 2XIIB, TMX and TMX-U, as well as a number of smaller machines.

Recently, we started in our laboratory at Johns Hopkins an evaluation program to determine the potential of layered synthetic microstructure (LSM) covered surfaces, as soft x-ray (10-350 Å) dispersive elements and narrow-band filters for fusion plasma diagnostic devices. These surfaces may be flat, in which case they are referred to as multi-layer mirrors (MLM), curved, or even a ruled flat, concave or toroidal grating. In collaboration with a group at the National Institute for Standards and Technology, we have measured, using synchrotron radiation, the properties of various types of MLMs produced by T. J. Barbee at LLNL, J. Underwood at Berkley Lawrence Laboratory and also those produced by the Ovonic Corporation. In February 1990, we mounted and operated on the TEXT tokamak a prototype MLM based spectrometer to study the intrinsic impurity (oxygen, titanium and iron) emission between 120-180 Å.

This prototype device will be followed (in 1991) by a high throughput-low resolution soft x-ray spectrometer for the 10-200 Å range for impurity behavior studies (radiative losses, accumulation, etc.) in the LH current drive/second stability regime experiments on the PBX-M tokamak at PPPL. An instrument which is similar in principle, but modified to suit the specific needs and constraints of a mainly molybdenum dominated emission from Alcator C-Mod is planned for construction in 1992 and will be operated on Alcator in 1992-93. In both cases, flat MLMs will be used as dispersive elements. Radiative power loss estimates will be determined by comparing the low resolution spectra with the predictions of collisional-radiative models for line emission of individual charge states coupled with transport codes, such as MIST. The use of these simple dispersive elements will make it possible to obtain many poloidal and toroidal views simultaneously; also, the high throughput of these systems - the MLMs are used at near normal incidence angles - will allow better time resolution than in previous experiments.

This year, in parallel with these developments based on flat MLMs, we started an intensive evaluation campaign of LSM coated curved surfaces. Such surfaces would enable either imaging of a large plasma volume at given wavelengths - e.g. motion pictures taken in oxygen Ly α emission at 19 Å - or tomographic imaging of a small plasma volume. Based on a preliminary feasibility study, described in detail later in the proposal, we propose an electron density and temperature fluctuation measurement in the center of the tokamak plasma. This diagnostic will use simultaneous measurements of $\Delta n=0$ and $\Delta n=1$ transitions of L-shell ions of intrinsic metallic impurities to estimate high frequency fluctuations of the above parameters. Again, this is only possible because of the high throughputs of LSM based instruments. As a first step with LSM imaging techniques, in 1991 we propose to install a plasma imaging device on the Phaedrus T tokamak in Wisconsin. It will use the oxygen emissions at 19 Å and 150 Å, to study the effect of the RF heating on the light impurities both in the scrape-off layer and deeper inside the plasma. The fluctuation measurement device will be built and laboratory tested during 1991 and installed (probably on TEXT) in 1992.

Following the Wisconsin experiments in which LSM coated curved surfaces will be used as dispersive and imaging elements, we plan to build in 1992, and operate by 1993, a device dedicated to the study of carbon pellet ablation during the final stages of the plasma-pellet interaction. Direct information on the ablation process would be obtained from radial and toroidal images of the carbon pellet using the HeI and HI-like, CV and CVI emission (at 40 Å and 34 Å, respectively). This diagnostic will also support the proposed use of such pellets for α particle confinement studies based on CXR measurements.

Within the framework of a subcontract to the Laboratory of X-Ray Spectroscopy at the Racah Institute of Physics, Hebrew University, Jerusalem, work has been started recently on the study of simple and versatile detection systems for the proposed MLM based experiments. Some of the most promising detectors will be first tested in laboratory in Jerusalem on small scale experiments, and then transferred to JHU for use in the full scale instruments.

In parallel with the above proposed developments, we will undertake a continuous effort towards the design of instruments based on LSMs for operation in harsh environments. Because of their simplicity, they will easily be handled/replaced by remote control. Also, because of their relatively low resolution output, simpler detectors can be envisaged. Spectroscopic diagnostics will be needed in future magnetic confinement devices both because (a) the decisive role of the control of the impurities in breakeven/ignition experiments and (b) because these diagnostics are non-perturbative.

The structure of the proposal is as follows: Section 2 describes recent progress on our research projects undertaken in late 1989 and 1990. They include besides the activities related to the MLM program, the study of the safety factor (on axis) q_0 and plasma current measurements performed on TEXT using Zeeman polarimetry; this experiment will be transferred to Wisconsin for the period TEXT will be shut-down for upgrade, and adapted to He beam operation.

Section 3 describes the proposed research mentioned briefly above and its methodology and planning over the next three years. Section 9 discusses the proposed budget.

II. Recent Progress

2.A.1. Laboratory experiments with flat MLMs.

After the reflectivity measurements performed in our laboratory and at NIST in 1989 (described in our previous proposal and references 1 and 2), the next stage was the test of the concept of a low resolution-high throughput MLM spectrometer in a small laboratory experiment. An important by-product of these laboratory experiments was finding the best way to block the UV and visible light by using various light blocking filter combinations.

A Penning Ionization Discharge (PID) was used as the laboratory source to measure radiation between 110-180 Å [3]. This region was of interest since it is roughly the domain in which iron and titanium, the dominant metallic impurities in many tokamaks, emit strong lines from 2-2 transitions of ions iso-electronic with Fe to LiI. The PID source is a cold cathode-reflex discharge used commonly with either aluminum or magnesium cathodes. In this particular experiment the cathodes were aluminum and the discharge gas was either argon or helium. The MLM-based spectrometer used a Mo/Si (2d=195.4 Å, N=40) MLM as the dispersive element except around the Si L absorption edge at 123 Å, where the reflectivity of the Mo/Si MLM is extremely small. For this region, a Mo/B₄C (2d=141.8 Å, N=60) MLM with a narrow bandpass of approximately 3 Å was the dispersive element. For comparison, the spectrum was also measured with a conventional 1 m. grazing incidence spectrometer with a resolution of less than 1 Å. This comparison, between the low resolution spectrum obtained with the MLM-based spectrometer and the high resolution spectrum of the grazing incidence spectrometer, is shown in Figures 1 and 2.

Figure 1. High resolution, grazing incidence spectrometer (a), and MLM spectra of a PID plasma in the 130-175 Å range (b, c).

In Fig. 1, the Mo/Si MLM was the dispersive element. Fig. 1a shows the spectrum obtained from the grazing incidence instrument while Figs. 1b and 1c were obtained with the MLM-based spectrometer in, respectively, an argon and a helium discharge. Between 160-175 Å the only lines are from AlIV 2p-3s transitions and AlIII 2p³s3p-2p⁶3p autoionization satellites. There are no lines from the discharge gases in this range. From the figure it can be seen that in an Ar discharge the resolution of the MLM is sufficient to distinguish the AlIV lines at 160 Å from the AlIII satellites around 170 Å. In a helium discharge, changes in the plasma parameters change the relative intensities of the lines at 160 and 170 Å and this is clearly indicated in the MLM-based spectrum of Fig. 1c.

Figure 2. Comparison between high resolution and MLM spectra in the 100-130 Å range.

Fig. 2 also presents a comparison of the MLM-based spectrometer and the grazing incidence spectrometer but this time, due to the wavelength region measured, the Mo/B₄C MLM was the dispersive element. The experiments were performed with helium as the discharge gas and the resolution of the MLM-based spectrum of Fig. 2 is such that it clearly distinguishes between the different charge states, their transitions, and their relative intensities. Thus, it is clear that if, for any reason, changes in the plasma parameters changed the relative intensities of different charge states, the low resolution spectrum obtained from the MLM-based spectrometer is sufficient to distinguish them.

In our most recent laboratory results using the MLM-based spectrometer, we measured the spectra from the PID between 160-350 Å [4]. This region is particularly interesting due to the fact that

it may be possible to use a MLM-based instrument as an alpha particle diagnostic by monitoring the 304 Å line (1s-2p) of HeII. Due to the large bandpass of this MLM, it was necessary to work in second order to distinguish the AlIV lines at 160 Å from the AlIII satellites at 170 Å, as shown in Fig. 3. On the other hand, these second order Al lines blend with the 304 Å HeII line making it necessary to produce a helium discharge with brass cathodes (brass has no lines around 160 Å) to measure the 304 Å line directly. This is shown in Fig. 4 which consists of a series of He/brass discharges. Note the 256 Å HeII feature appears in some spectra, depending on discharge conditions. Again, the conclusion of this experiment is that meaningful information about the plasma emissions can be extracted from the low resolution spectra.

Figure 3. Mo/Si MLM spectrum from the PID around 304 Å

Figure 4. MLM spectra from PID under various plasma conditions; the unblended HeII line at 304 Å clearly changes in intensity and shape.

2.A.2. Tokamak (TEXT) experiment with flat MLM.

To determine whether these MLMs would be suitable for the demanding environment and complex spectra of a tokamak discharge, a similar MLM-based spectrometer to that described in 2.A.1. was recently mounted on the Texas Experimental Tokamak (TEXT). Discharges lasted for 600ms. with a plateau of 400ms. A series of experiments were performed which measured the spectra from the tokamak from 90 to 180 Å [5]. The prototype spectrometer, as well as the beamline used when it was mounted on the TEXT tokamak, is shown schematically in Fig. 5. The spectrometer is housed within

Figure 5. Schematic of the TEXT Experimental Set-Up.

a 20" diameter vacuum tank. As indicated in the figure, to perform a wavelength scan with this instrument it is necessary to change the incident angle of the incoming radiation which strikes the MLM. This was accomplished by mounting the MLM and the detector on a Θ - 2Θ goniometric table consisting of two 360° rotators, stacked concentrically, which allowed for the movement necessary to perform such a scan. A filter wheel was mounted outside of the spectrometer's vacuum chamber and made it possible to insert an 0.8μ beryllium or a 0.9μ boron/parylene filter into the beamline to limit the noise due to longer wavelength ultraviolet and visible radiation. Depending on the particular experiment, the entrance slit was adjusted so that the maximum photon flux entered the vacuum vessel without saturating the channeltron detector. For these experiments, the entrance slit was 1 mm. wide and 2-6 mm. high which is more than an order of magnitude larger than an entrance slit of a typical grazing incidence soft x-ray spectrometer. Thus, this type of instrument is ideal for diagnostics where high throughput is necessary while a high resolution is not critical. The emission of titanium, the main high Z intrinsic impurity in TEXT, was measured between 130 to 180 Å. The data was obtained by placing a Mo/B₄C (2d=187.4 Å, N=75) MLM at the appropriate Bragg angle on a shot-to-shot basis. To eliminate the effect of the plasma conditions and equilibrium, titanium was introduced during the steady state phase by the laser blow-off method and a purely titanium spectrum was produced by subtracting the background spectrum immediately before the laser pulse. The results from a series of He discharges ($B_T=28$ kG, $I_p=200$ kA, $n_e=2 \times 10^{13} \text{ cm}^{-3}$) is presented in Fig. 6. The shape of the experimental curve is dominated by emission of

Figure 6. TEXT tokamak spectrum recorded with the MLM spectrometer in the 130-180 Å range.

Figure 7. Synthetic spectrum obtained from IE calculations and taking into account the bandpass of the mirror (measured).

high charge states of TiXIX ($\lambda=169.6 \text{ \AA}$) and TiXV-XVIII (around $144 \text{ \AA}$). This identification is made from a comparison of the data with the spectra shown in Fig. 7; this is a plot of the strong Ti lines between $135\text{-}180 \text{ \AA}$ with the assumption that the lines are gaussian in shape with a FWHM equal to the bandpass of the MLM and a relative amplitude based upon a collisional-radiative model under equilibrium conditions [6]. The small discrepancy between the experimental and calculated curves is due to OV emission at $150 \text{ \AA}$ and $173 \text{ \AA}$ which blends together with the titanium lines due to the bandpass of the MLM. This effect can be seen in Fig. 8 which consists of a Ti spectrum and then the addition of various amounts of oxygen to the titanium spectrum. From this matching of the 'theoretical' and experimental spectra it is possible to deconvolute the Ti emission. Thus, this "proof of feasibility" experiment has shown that it is possible to interpret a low resolution tokamak spectra obtained from this prototype MLM instrument, and that it would be possible to identify changes in the titanium emission due to changes in the plasma parameters in a spectrum as complicated as that obtained from a tokamak.

Figure 8. The effect of adding oxygen to a purely titanium spectrum.

2.B. Li beam space and time resolved Zeeman polarimetry with narrow bandpass filters.

The principle of the measurement and previous results using a Fabry-Perot interferometer have been extensively discussed in previous publications [7-10]. In these experiments the accuracy of the poloidal field measurements was 50G (in discharges with electron densities of $1.5 \times 10^{13} \text{ cm}^{-3}$); the measurement was not time resolved because the Fabry-Perot interferometer scanned a spectral line profile at a rate of $\sim 200 \text{ msec}$ per interference maximum. In order to obtain time resolution and thus be able to study the evolution of q_0 , we built a new polarimeter based on very narrow bandpass filters.

The schematic of the filter based polarimeter is shown in Fig. 9. The transmission peaks of two interference filters with bandpasses of about 2.5 Å are respectively set at a wavelength near $\lambda_0 \pm \lambda_0 \sqrt{2}$; the photoelectron current of the two channels are added at the output. Thus the peak value of the modulation, $\max(I_L - I_R)$, and a fraction of the line peak intensity $I(\lambda_0)$ can be continuously measured. We remind the reader that the peak modulation is:

Figure 9. Schematic of the filter based Zeeman polarimeter.

$$m_p \equiv \text{const} \frac{I(\lambda_0) \cos \theta \lambda_B}{\Delta \lambda} \propto B \cos \theta$$

$$\text{since,} \quad \Delta \lambda_B = Z \frac{\mu_0 \lambda_0^2 B \Delta M}{2\pi \hbar c}$$

$$\text{We obtain:} \quad B_m \equiv B \cos \theta \equiv \text{const} \frac{m_p}{I(\lambda_0)}$$

Thus, the modulation signal is proportional to the magnetic field projection in the direction of observation; if this is in the poloidal plane, the poloidal field is measured.

The filters were kept at a constant temperature of $21.8^\circ (\pm 0.1^\circ \text{C})$ by means of a water circulating system. This ensured a wavelength stability of $0.019 \text{ \AA}$. At the modulation peaks, the profile is very flat so that a $0.02 \text{ \AA}$ wavelength drift will result only in a 1% drift on the peak modulation. The proportionality constant in the above formulae, stabilized by the thermal stability of the system, was calibrated against the known toroidal magnetic field at each radial position of the measurement.

The new technique increased the diagnostic sensitivity, and reduced the integration time for the measurement to about 16 msec. with a 100 keV and 1 mA lithium beam. The measurement is continuous, enabling to monitor transient processes in the tokamak plasma, such as the electron cyclotron heating (ECRH). The radial spatial resolution of the diagnostic is 1 cm.

The polarimeter was equipped with remote control. It could therefore be operated in the tokamak control room without interrupting other experiments.

With this new apparatus we measured q_0 values for Ohmically heated discharges as well as high edge q_0 discharges with ECRH. The results, listed in Table 1, are consistent with our previous findings, i.e., that the q_0 values for all Ohmically heated discharges are near unity regardless of the sawtooth activities. ECRH at the magnetic axis drove the plasma current to the center, thus bringing the q_0 values significantly below unity. The measured B_q profiles are presented in Fig. 10.

By measuring the position of the magnetic axis, the polarimeter also determined the increment of the Shafranov shift during the ECRH discharges; higher electron temperature during ECRH, leading to higher plasma pressure, pushed the magnetic axis outward by $0.7 \pm 0.4 \text{ cm}$. From this measurement, we estimated the ECRH power deposition independently.

Figure 10. The measured B_0 profiles for the 21.6kG/114kA/1.4H/ ECRH=160kW discharges on TEXT, May 23, 1990. The solid curve is the fitted B_0 , q and j profiles are derived from B_0 . Left, the measurement taken before ECRH. Right, the measurement taken during ECRH.

Table I. Recently Measured q_0 Values

$B_0/I_p/\sqrt{n_e}$	H ^b	STA ^c	$q_0 \pm \Delta q_0$	Fit ^d	Mon/Day/Yr
21.6/120/1.5	O	N	0.99 ± 0.06	P	05/21/90
21.6/120/1.5	O	N	1.00 ± 0.09	P	05/22/90
21.6/120/1.5	O	N	0.99 ± 0.08	P	05/22/90
19/120/1.5	O	N	0.98 ± 0.12	P	05/22/90
17/120/1.5	O	Y	1.19 ± 0.17	L	05/22/90
15/120/1.5	O	Y	1.06 ± 0.08	L	05/22/90
21.6/110/1.4	O	N	0.98 ± 0.09	B	05/23/90
21.6/110/1.4	E	N	0.66 ± 0.05	B	05/23/90

- a: Discharge condition: toroidal magnetic field B_t in kG, plasma current I_p in kA, line averaged electron density $\bar{n}_e$ in 10^{13} cm^{-3} . All measurements were made for the hydrogen discharges.
- b: O stands for Ohmical heating, and E for ECRH at the magnetic axis.
- c: SawTooth Activities: Y if STA exist, N if STA do not exist.
- d: Fitting procedure: B stands for the $B_\theta(r)$ fitting of the locally measured B_θ profile, P for a parabolic function fitting of the locally measured B_θ profile inside $r = 12 \text{ cm}$, and L for a straight line fitting of the measurements inside the sawtooth inversion radius.

2.C. A Feasibility study of an XUV spectroscopic measurement of electron density and temperature fluctuation in the tokamak plasma center.

In this subsection we briefly present the principal ideas underlying the proposed measurement. Details are given in the Appendix and the instrumental aspects are described briefly in section 3.B.1.

Energy-loss rates in tokamaks were found a long time ago to be one to two orders of magnitude larger than those predicted by the (neo) classical collisional transport theory calculated for the tokamak magnetic field geometry [11]. This huge loss, referred to as the anomalous loss, is assumed to be caused by 'anomalous' electron particle diffusion and electron thermal conduction. Understanding and controlling the anomalous transports are essential for the improvement of the tokamak energy confinement. Several theoretical approaches and experimental evidence have suggested that microturbulence might account for the anomalous transports in the tokamak plasmas [12]. The measurable physical quantities related to microturbulence are the fluctuations of the electron density, electron temperature, electrostatic potential and radial magnetic field, and correlations among the fluctuations. From the fluctuation measurements, one can infer the electron diffusion coefficient and the thermal conductivity. So far, however, such measurements have been restricted primarily to the plasma edge.

We suggest a spectroscopic method for measuring both the electron density and temperature fluctuations, $\bar{n}_e$ and $\bar{T}_e$, respectively, in the high temperature region of the tokamak plasma. The diagnostic is based on measurement of emissivities of pairs of spectral lines originating from resonant transitions of highly ionized intrinsic impurities. The emissivities of the chosen lines depend linearly on both $\bar{n}_e$ and $\bar{T}_e$ when the fluctuations are small and at high frequency. The spectral lines will be measured simultaneously by two pairs of monochromators, having LSM coated surfaces as dispersive elements, with their lines of sight crossing in a small plasma volume. It can be shown (see detailed discussion in Appendix I) that correlations between the signals can provide localized measurement of $\langle \bar{n}_e^2 \rangle$, $\langle \bar{T}_e^2 \rangle$ and $\langle \bar{n}_e \bar{T}_e \rangle$ in the small central plasma volume.

There are non-spectroscopic techniques for measuring such fluctuations, based on various types of probes [13], electromagnetic wave scattering [14], and the heavy ion beam probe (HIBP)[15]. Each technique has been partly successful, but all have various limitations [see for instance discussion in

references 12 and 16]: probes can measure fluctuations only in low temperature plasmas mainly at the edge, the electromagnetic wave scattering can explore $\tilde{n}_e$ in high temperature plasmas but with low spatial resolution. The HIBP can simultaneously measure $\tilde{n}_e$ and electrostatic potential fluctuation, but the interpretation of its signals is complicated. No diagnostic exists at the present time for measuring $\tilde{T}_e$ for the microturbulence study in the central tokamak region.

According to the present knowledge, the microturbulences are characterized by broadband fluctuations at high frequencies (~ 200 kHz) [12, 16]. The correlation length of the microturbulent fluctuations is on the order of 1 cm. Magnitudes of both $\tilde{n}_e/n_e$ and $\tilde{T}_e/T_e$ could be as low as a few tenths of a percent in the tokamak central region, and increase to values on the order of 10% at the plasma edge. The measurement of the fluctuations should be taken as averages over a period that is sufficiently long compared with the characteristic time of microscopic changes, and shorter than the period for the macroscopic changes in plasma. For a medium size tokamak, such as TEXT, the steady state phase of the Ohmically heated discharges lasts a few hundred milliseconds. [17]. During this phase the plasma current, the electron density, the electron temperature, and plasma radiation intensity remain constant. For the study of some transient plasma conditions, such as those during auxiliary heating or gas puffing [18, 19], again under TEXT conditions, the required time resolution for the diagnostic should be a few milliseconds. The above values define the requirements for the proposed spectroscopic diagnostic insofar as the response time, the spatial resolution, the accuracy, and the integration time are concerned.

Spectral lines listed in Table 1 in Appendix I are chosen as candidates for the diagnostic. These spectral lines, originating from both $\Delta n = 0$ (from $n = 2$ to $n = 2$) and $\Delta n = 1$ (from $n = 3$ to $n = 2$) resonant transitions of Li I-like to Fl I-like ions of intrinsic titanium and iron, emit in the extreme ultraviolet (XUV) range (10-350 Å) [20, 21]. These charge states exist and emit in the high temperature (1-1.5 keV) central tokamak plasma. The radiative transitions are much faster than the fluctuations and strong. As will be discussed in detail in Appendix I, simultaneous measurement of both $\Delta n = 1$ and $\Delta n = 0$ resonant transitions will be required to decouple $\tilde{T}_e$ and $\tilde{n}_e$ in the spectral signals. The $\tilde{n}_e$ and $\tilde{T}_e$ dependence of the spectral emissivity are linear and well understood, as shown in the appendix. The magnetic dipole transitions and other 'forbidden' transitions, even though emitting in the near-ultraviolet and visible spectral range, are too 'slow' [22] and transitions from highly excited states populated by the charge-exchange and recombination processes are difficult to be modeled for the $\tilde{n}_e$ and $\tilde{T}_e$ measurements [23]. In order to detect the fluctuations of $\sim 1\%$, the monochromators must have high throughput in the XUV region. As mentioned already, the existence of layered synthetic microstructures (LSM) deposited flat and curved surfaces will make these measurements technically possible: they will provide in fact a reflective filter with a bandpass of a few Å and peak-reflectivities as high as 60% near normal incidence [2, 3].

Appendix I will discuss in detail the spectroscopic aspects of the dependence of the spectral line emissivity on $\tilde{n}_e$ and $\tilde{T}_e$. The relations between the correlation of the line intensities and the quantities $\langle \tilde{n}_e^2 \rangle$, $\langle \tilde{T}_e^2 \rangle$ and $\langle \tilde{n}_e \tilde{T}_e \rangle$ and estimates of the signal-to-noise ratio for the proposed diagnostic.

III. Proposed Research

The summary of the proposed projects for the three-year period, 1991-93, is as follows:

- (a) Finalize design and build flat MLM based spectrometers for impurity behavior studies in the 10-200 Å range on PBX-M and Alcator C-Mod .
- (b) Design, test and mount on on Phaedrus T and Alcator C-Mod tokamaks, LSM coated curved surface based devices for plasma and pellet penetration/ablation imaging in the 10-200 Å range.
- (c) Build, test first in the laboratory and then mount on TEXT (or other tokamak) a system for electron density and temperature fluctuation measurements in the center of the tokamak plasma based on line emission correlation measurements using LSM coated curved and flat surfaces.

These projects involve the evaluation of the optical components, to be done both in our laboratory at Johns Hopkins and using the SURF synchrotron beam line at National Institute for Standards and Technology. Specific solutions for the detecting systems of each of the proposed diagnostics will be worked out partly at Johns Hopkins, partly at the Hebrew University in Jerusalem, and partly in collaboration with scientists on the Phaedrus T, PBX-M, Alcator C-Mod and TEXT projects in Wisconsin, Princeton, MIT, and Austin.

The LSM coated surfaces will be either purchased from commercial suppliers or subcontracted with T. Barbee, Jr. at LLNL.

Prototypes of the above instruments will first be set up in our laboratory at JHU and tested prior to tokamak operation using laboratory sources developed and/or under development at JHU. In some cases when our sources will not be adequate for these tests, we will test components by integrating them in prototype devices to be used on tokamaks. We plan to have each graduate student and/or postdoctoral fellow responsible for a given experiment, spend a brief period of time on the experiment with which he will be involved prior to the building of the actual instrument. This, together with the fact that we already discussed, and will keep discussing as the projects advance, all the details with representatives of the respective groups, will ensure a diagnostic well adapted to the needs of the individual programs.

The proposed time schedules are as follows:

- 1991: (1) Design and implementation of the MLM array for PBX-M; operation on PBX-M during the last part of the year by an advanced graduate student.
- (2) Study of the reflectivities and optical properties of LSM coated curved surfaces in the 10-200 Å range, mainly in our laboratory at JHU and at NIST.
- (3) Design and implementation of an oxygen Ly α and OV imaging device for Phaedrus T and operation by a JHU graduate student in collaboration with R. Fonck and a Wisconsin student during the second part of the year.
- (4) Study of various detecting systems for the fluctuation/next stage devices at JHU and H.U. in Jerusalem.
- (5) Final design of the system for fluctuations and set-up and test of a Kirkpatrick-Baez imaging device using LSM coated curved elements in the 10-20 Å range.
- 1992: (1) Implementation of the system for fluctuation studies; test at JHU and operation on TEXT, or other tokamak.
- (2) Design and implementation of the MLM-Molybdenum monitor for Alcator C-Mod. Operation on tokamak by the last quarter of the year.
- (3) Design of an imaging system at 34 Å and 40 Å for carbon pellet ablation studies in CV and CVI light.
- 1993: (1) Implementation of the imaging system for carbon pellet ablation studies and operation on Alcator C-Mod.
- (2) Operation of the fluctuation study system on TEXT (or elsewhere); adaptation, if successful, for next generation machine.
- (3) Operation of the Molybdenum monitor on Alcator C-Mod.
- (4) Planning and design of remote controllable devices for CIT.

In the following we will discuss in more detail the proposed devices. We would like to emphasize again that all of them are going to be built in tight collaboration with the designated experimental group to ensure a best adaptation to the scientific program and specific machine requirements.

3.A. Soft X-ray normal incidence spectrometers/filter arrays based on flat multilayer mirrors (MLMs).

3.A.1. Principle of operation.

At the most general level, the idea - as explained in sections 2.A.1. and 2.A.2. - is to use MLMs as dispersive elements and thus enable high throughput-near normal incidence XUV spectroscopy to replace or in some cases complement the previously used grazing incidence spectrometers. The MLM based systems can be located at various toroidal and poloidal locations, and as will be explained in the next subsection for the case of the PBX-M system, the set-up and the optical alignments are very much simplified in the proposed devices comparatively with grazing incidence geometries.

The question is how can the low resolution spectra of the type presented in section 2.A.2. be used to extract meaningful information about the impurity content of the tokamak plasma.

Consider again the TEXT spectrum of Fig. 6; the "synthetic" spectrum shown in Fig. 7, obtained by enlarging the Ti lines emitted in this range to the width given by the measured bandpass of the mirror used, is slightly shifted compared with the experimental one. As shown in Fig. 8, the discrepancy between this and the experimental spectrum of Fig. 6 is accounted for by adding the OV lines at 150 Å and 173 Å. One can clearly see from Fig. 8 that the low resolution spectrum is quite sensitive to the addition of the two individual oxygen lines. A further relative increase of the oxygen content relative to titanium would skew significantly the peaks at 145 Å and 170 Å. If there would be large amounts of iron in the plasma, the oxygen line at 173 will be blended with FeIX emission ($\lambda=171$ Å) and some other low iron charge states, but the line at 150 Å would be unblended. Therefore, the low resolution spectrum under discussion enable to tell which are the dominant impurities in the plasma and what is their relative weight. Since the $\Delta n=0$ TiXIV - TiXIX line ratios between 140 Å and 170 Å are not electron temperature sensitive (see the extensive discussion on the subject in ref. 24), the relative intensity of the two peaks will not change significantly due to an enhanced transport of titanium ions; that is why in order to obtain transport information, one will have to measure in parallel with $\Delta n=0$ emission, some temperature sensitive, $\Delta n=1$ lines at shorter wavelengths.

It is important prior to the design of the MLM based device to specifically define the question to be asked about the impurity content. For instance, in PBX-M, the questions could be whether the impurities accumulate in the center during NBI heating experiments, or whether the overall impurity content will change during LH heating or by increasing the plasma indentation. In other experiments, such as Alcator C-Mod, where the inner bumper limiter and the diverter plates will be protected by molybdenum tiles, it will be important to be able to estimate at any stage of the program the total radiative power loss due to molybdenum ions.

For the first set of questions, it is enough — after having established which are the main 'heavy' and 'light' impurities, to monitor the $\Delta n=0$ emission of the L-shell ions and the $\Delta n=1$ - temperature sensitive emission of the NeI-like ion. This case will be discussed in more detail as applied to the PBX-M device, in section 3.A.2.

In the case that absolute power loss measurements are required, it will be necessary to couple the experimental data with theoretical computations. Radiative losses in the hot core of the tokamak plasma are primarily due to line emission from charge states iso-electronic with LiI to NeI. For instance, the ionization potentials of the corresponding nickel ions range between 1.5 keV and 2.5 keV respectively. The 2-2 transitions (such as $2s^2 2p^* \rightarrow 2s 2p^{*+1}$), of these L-shell ions are concentrated in the 80 to 200 Å range for the typical tokamak metallic impurities, titanium, chromium, iron and nickel. For instance, Ni XX (Fe-like) emits its strongest 2-2 line at 83 Å, Ni XXVI (Li-like) at 164 Å, while the corresponding titanium lines are at the other end of the spectral range at 122 Å and 259 Å.

Global radiative loss estimates are obtained by summing the measured energies radiated in individual lines originating from $\Delta n=0, 1, 2$, etc., transitions emitted from all the charge states present in the plasma. In principle that would imply simultaneous measurements in the 2 Å to 400 Å range. Photometrically calibrated instruments of various types (crystal, grazing and normal incidence) would be needed to cover this entire range. In practice, due to a fairly good understanding of the radiative patterns of tokamak plasmas accumulated over the last 15 years (see for instance the review articles of DeMichelis and Mattioli [25], and Isler [26]), only a few prominent lines of each of the mentioned charge states are measured, typically in the 100-300 Å range. Using the fractional abundances predicted by impurity transport codes and collisional radiative models for the level populations of individual charge states together with independent electron density and temperature estimates, one can add the contribution of the lines which could not be measured. However, since the transport may be anomalous under some experimental conditions, if one cannot establish the radial position of the emitting ions in one single shot (required precisely in order to sort out the effects of enhanced transport), one needs as already mentioned, the measurement of $\Delta n=1$ transitions sensitive to the electron temperature. In the case of iron group elements, we will measure the NeI-like emission, $2p^6 \rightarrow 2p^5 3s, 3d$ in the 10-20 Å range, in the case of molybdenum, $\Delta n=1$ emission of M-shell ions in the 10-50 Å range.

We plan to set up at JHU the needed data base for such calculations; we have already obtained from R. Hulse (at PPPL) a version of the MIST transport code, and Dr. A.K. Bhatia at Goddard Space Flight Center will provide the atomic data needed in the collisional-radiative calculations. The analysis of the Ti emission on TEXT is in process and will be presented at the 1990 APS meeting.

The next two subsections discuss in more detail the two specifically proposed experiments on PBX-M and Alcator C-Mod.

3.A.2. Near normal incidence spectrometers for impurity studies in LH current drive, high β plasmas on PBX-M.

In most of the experiments proposed under the PBX-M program, the impurity behavior will play an important role. In previous PBX experiments it has been observed that in high β plasmas, impurities accumulate on the axis [27]; moreover, in parallel/counter-NB injection, high Z impurities were also strongly peaked on axis. Since changes in the impurity content associated with changes in the current profile during LH current drive experiments, would in turn lead to changes in the electron temperature profile, it will be important to infer such possible changes from the impurity radiation patterns. All these require not only the ability to measure the central impurity concentration and its change in time, but also changes in the emissive shell distribution.

A survey instrument of the SPRED type available on PBX-M cannot perform these tasks for the following reasons: it does not cover the range below 100 Å, it does not have a radial scan capability, and it is not photometrically calibrated over the entire spectral range of interest. On the other hand, by recording at higher resolution some of the central ion emissions, SPRED will complement our proposed system.

Figure 11. Schematic of the MLM array for monitoring impurity behavior on PBX-M tokamak.

The array system we propose is shown schematically in Fig. 11 and consists in fact of two parts; a system to monitor the plasma center horizontally and a vertical system to monitor the shell of NeI-like ions. Horizontally, the dispersive element will be a large flat MLM coated with strips of different 2d spacings, chosen in such a way that at a given angle it will cover the entire spectral range of interest above 100 Å. This soft x-ray spectrum is 'translated' into a visible one by using a P20 phosphor coated MCP and the visible photons are then transferred to the photodetectors by a coherent fiber optics bundle (a technique extensively used nowadays in soft x-ray plasma spectroscopy). This element of the system will record the L-shell emission spectrum of the main metallic impurity in the 100-200 Å range. Since the optical filters (not shown in figure, used to cut off visible and UV light), the MLMs and the detectors will be individually calibrated prior to the experiment. The entire system will be photometrically calibrated. Thus, although the primary emphasis will be on changes in impurity concentration, absolute values will also be obtained.

For the vertical view, a movable (horizontally) collimator-mirror system will make it possible to monitor the shell emitting the temperature sensitive NeI-like lines, between 10-20 Å (depending upon the Z of the main 'heavy' impurity, e.g., 12 Å and 14 Å for NiXIX or 15 Å and 17 Å for FeXVII). Most of these lines are unblended — the iron line at 17 Å could be contaminated with Lyβ OVIII emission. However, the resolution of these mirrors can be quite high; with 100 layers a W/C mirror would have a theoretical resolution of 0.1 Å to 10 Å ($\frac{\lambda}{\Delta\lambda} \sim N$, N being the number of layers).

The interpretation of the spectra will rely on the fit of the results of transport codes and collisional-radiative models for the L-shell ions to the experimental data. The successive steps in the data analysis will be:

- (1) Identify the main metallic impurities and sort out the blends with light impurities (as shown in the discussion of the TEXT spectra.).
- (2) Assuming *ab initio* calculated collisional excitation and radiative decay rates for main transitions of the L-shell ions, anomalous diffusion coefficients and inward convective velocities in the transport codes, fit the predicted line intensities to the experimental ones. Since the electron density profile is independently measured, this fit will 'pin down' the electron temperature at which the ions emit.
- (3) At this point, if power loss estimates are required, these will be calculated as $P_{\text{tot}} = \sum_{\lambda \neq 0} P_{\text{line}}$
- (4) Changes in the temperature profile will be inferred from the spatial variation of emission of NeI-like ions and the changes in relative intensities of these and the (FI to BeI-like) ions emission measurements.

3.A.3. An array of narrow band soft x-ray filters for molybdenum radiative loss estimates on Alcator C-Mod.

The emission patterns of molybdenum ions in tokamaks with $T_e(0)=1-2.5\text{keV}$, have been studied in the soft x-ray range on TFR, Alcator A and C, DITE, PLT and JFT2 tokamaks. Basically, the ions with the $3d^*$ sub-shell open radiate between $50\text{ \AA}$ (NiI-like, MoXV) and $30\text{ \AA}$ (MoXXIII); these are charge states with ionization potentials of the order of $100-300\text{ eV}$ which emit from the edge. The $3p^*$ sub-shell ions MoXXIV to MoXXX (IP of several hundreds eV), emit between $70-85\text{ \AA}$. Finally, the high charge states, MgI and NaI-like MoXXXI and MoXXXII emitting at about $1.5-2\text{ keV}$, have strong resonance features above $100\text{ \AA}$ [28, 29].

This emission distribution is very well suited for low resolution work. Indeed, a flat MLM optimized at $40\text{ \AA}$ with a bandpass of $2-4\text{ \AA}$ will record emission characteristic of the plasma edge, whereas mirrors centered at $75\text{ \AA}$ and $130\text{ \AA}$ will monitor intermediate and central state emissions. In the case, for instance, of RF heating experiments with high central electron density, the main interest would be in monitoring the level of impurities during the wave heating. Local sources — such as the RF antennas and the limiter — play an important role in impurity production and one would like to see their contribution to the impurity density.

We propose to set up on Alcator C-Mod arrays of narrow band MLM filters at $40, 75, 120\text{ \AA}$ to monitor poloidal and toroidal molybdenum distributions. At each location, three different mirrors will filter out and reflect the above-mentioned emission. The soft x-ray light will then be handled as in the PBX-M experiment.

3.B. XUV spectroscopic measurement of electron density and temperature fluctuations.

In section 2.B.3. and Appendix I, we presented a detailed discussion of the theoretical feasibility study of these measurements. Here we will briefly discuss the experimental aspects of the proposed measurement. As already explained, the measurement is based on the electron density and temperature dependence of the spectral line intensities of intrinsic metallic impurities. The curved LSM coated surfaces enable spectrometers to have high throughput and focus on a small emitting volume element in the plasma center. The proposed crossing-view correlations of spectral line intensities can extract the signals of local $\bar{n}_e$ and $\bar{T}_e$ from the line-integrated intensity. The measurements will be performed at $169\text{ \AA}$ and $17\text{ \AA}$ in the case of titanium emission, in order to obtain the temperature fluctuation. Fig. 12 shows a schematic drawing of the four monochromators mounted on a tokamak in order to image the central plasma at these two wavelengths.

We propose to use two different types of monochromators for the two wavelength ranges. In both cases, since the correlation length of the fluctuations is about 1 cm. , the field of view in the plasma will be of the same order and adjustable. The imaging resolution is 0.1 cm. The throughput requirements lead to f numbers of $f/9.8$ for the long wavelength systems and $f/8.4$ at $17\text{ \AA}$. The wavelength resolution is $7\text{ \AA}$ at $169\text{ \AA}$ and $1\text{ \AA}$ at $17\text{ \AA}$. Figs. 13 and 14 show the proposed design of the spectrometer at long wavelengths and the Kirkpatrick-Baez mount for imaging at short wavelengths. In both figures, the origin of the coordinates is at the incidence point on the first reflecting surface. The optical axis are characterized by r , their orientation by the normal n , in a frame in which Oz is the incident optical axis of the system.

Figure 12. Schematic of the 4-monochromator correlation measurement proposed for electron density and temperature fluctuation estimates.

The feasibility analysis discussed in section 2 has been performed for an OH plasma having a central electron temperature of the order of 1 keV, and the main high Z impurity, titanium. The steady state phase of the discharge should be of the order of several hundreds of milliseconds. A very plausible candidate would therefore be TEXT and we worked having this tokamak in mind. However, the design allows some minor modification for operation on a different tokamak if needed.

Tests of main components for the spectrometers will be completed this year. Prototypes of the spectrometers will be tested in our laboratory by mid 1991.

Figure 13. High throughput monochromator at 169 Å using LSM Reflector at 10° Incidence.

Figure 14. High throughput monochromator at 17 Å using LSM reflector and Kirkpatrick-Baez structure.

3.C. Plasma imaging and pellet ablation studies using curved LSM coated surfaces.

The proposed systems are similar in principle, but the applications of the two are quite different. In one case we propose to image the Phaedrus T plasma in OVIII Ly α emission at 19 Å and OV emission at 150 Å, in order to study the impurity penetration during RF heating experiments. In a $T_e(0) = 600\text{--}800\text{ eV}$ expected in Phaedrus T, OVIII will be 'central,' whereas OV will emit at the edge. Quantitative brightness measurements, coupled with the deconvolution of the charge state distribution from the plasma images obtained will enable to distinguish between an overall increase in the impurity content, and/or a redistribution of the emitting shells due to temperature profile changes following the RF pulse.

Figure 15. Schematic of a plasma imaging device for Phaedrus-T tokamak.

The schematic of the imaging device is presented in Fig. 15. In principle a single mirror could be used as shown in the figure, but the quality of the image would be better if a second curved mirror were added. The position of the mirror has to be chosen in such a way that the divergence around the Bragg angle will be minimal. The visible light blocking filter will be similar to that used in the TEXT experiment described in section 2. The light will be extracted in a similar way in the x-ray imaging experiment performed by R. Fonck et al. on PBX [30] (and as already agreed, this equipment will be provided by the Phaedrus T group).

The second application, during the second half of our proposed program, will be to image the final stages of carbon pellet ablation processes. Quite a bit of work has been done on pellet fuelling and penetration and carbon pellets have been proposed for use in a particle confinement studies. Most of the pellet imaging work has been done in the visible and the conclusions concerning the pellet-plasma interaction are ambiguous to a large extent. Of special interest would be the study of the final stages of the disintegration process; that is why we propose to set up an imaging system to monitor both the radial and the toroidal penetration of CV and CVI clouds by imaging them at 34 and 40 Å with curved multilayer mirrors.

Whereas the imaging system would be very much like the one described above for Phaedrus T, we still have to study the performance of LSMs at the above-mentioned wavelengths. The problem is that the best mirrors in this domain are W/C ones; however, as we approach the carbon absorption edge, 44 Å, their performance becomes poor and a replacement has yet to be found. A boron nitride-vanadium mirror performed reasonably well at 25 Å [31], but we do not know its behavior above this wavelength. This experiment is planned for Alcator C-Mod.

IV. References

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Appendix I

I. Spectral line emissivity as a function of $\bar{n}_e$ and $\bar{T}_e$

The spectral line emissivity is defined as

$$\epsilon_{jk} = \frac{1}{4\pi} A_{jk} P_j n_z \quad (1)$$

where A_{jk} is the radiative transition rate from level j to k , P_j is the fractional population of the upper level j , n_z is the ion number density, and ϵ_{jk} is in units of photons/cm³ · sr · sec. A_{jk} is a constant under the tokamak plasma conditions. P_j and n_z are determined by various physical processes in the plasma, especially by electron-ion collisions. Thus, they are generally functions of both the electron density and the electron temperature. We will derive relations between the emissivity ϵ_{jk} and both $\bar{n}_e$ and $\bar{T}_e$ for the microturbulent fluctuations.

Table 1 lists candidates of spectral lines of the titanium and iron ions for this diagnostic. Ionization equilibrium temperatures for these ions are also listed in the table.¹ Typical electron temperature in a medium size tokamak is about 1 keV at the center and about 10 eV near the edge, and the average electron density is about 3×10^{13} cm⁻³.² The titanium and iron atoms are sputtered off the vacuum vessel, then diffuse into the plasma. Various charge states are distributed in radial shells according to their ionization equilibrium temperatures.¹

Upper levels of the transitions in Table 1 are primary populated by electron collisional excitation from a ground level or from both a ground level and some low-lying metastable levels. The level populations under consideration are close to coronal equilibrium under the steady tokamak plasma condition.³ In order to analyze the effect of microturbulence on the level populations, consider the Ti XIX $2s^2 \ ^1S - 2s2p \ ^1P$ transition at 169.6 Å as an example. The $2s2p \ ^1P$ state is excited from the ground state $2s^2 \ ^1S$ by the electron collisions. Other atomic processes, such as collisional deexcitations and radiative cascades, contribute to the $2s2p \ ^1P$ level only 10^{-4} of its population, thus they are negligible.^{4,5} This

justifies a two-level model: the $2s^2\ ^1S$ and $2s2p\ ^1P$ levels are coupled only by the collisional excitation and the radiative decay, and their level populations are not affected by other atomic processes. Thus,

$$\frac{dP_j}{dt} = C_{gj}n_e P_g - A_{jg}P_j, \quad (2)$$

where subscripts g and j indicate respectively the ground level and the excited level, C_{gj} is the collisional excitation rate, and P_g is the ground level population. Using conditions $P_g + P_j \simeq 1$ and $C_{gj}n_e/A_{jg} \sim 10^{-5}$, one can replace Eq. 2 by

$$\frac{dP_j}{dt} = -A_{jg}P_j + C_{gj}n_e. \quad (3)$$

The above two level model can also be used for the levels involving electron collisional excitations from both the ground state and the low-lying metastable states in our cases. For instance, the $2s3d\ ^3D$ levels of the Be I-like ion are mainly populated by the electron collisional excitations from both the $2s^2\ ^1S$ state and the $2s2p\ ^3P_0$ state. Radiative transitions from the $2s2p\ ^3P_0$ state are totally forbidden. (The $2s2p\ ^3P_0$ is thus a stable state rather than 'the metastable state', however, we use it as an extreme of other low-lying metastable states.) Thus, the relative population for the two states is closer to Boltzmann equilibrium rather than the coronal equilibrium, and approximately independent of the electron density. The relative population changes by only $\sim 2\%$ when n_e increases from $4 \times 10^{13}\text{ cm}^{-3}$ to $1 \times 10^{14}\text{ cm}^{-3}$ according to numerical computations.⁴ We can rewrite the electron collisional excitations, $C_{gj}n_e P_g + C_{mj}n_e P_m$, as $[C_{gj} + C_{mj}f(T_e)]n_e P_g$, where the subscript m indicates the metastable state, and $f(T_e)$ is a weak function of T_e and approximately equal to unity because the energy gap between the g and m levels is less than $0.05T_e$. $[C_{gj} + C_{mj}f(T_e)]$ depends only on T_e , and can be treated as an analogy to C_{gj} for the two level model in Eq. 3.

In Eq. 3, both C_{gj} and n_e are functions of time t because of the microturbulence.^{6,7} It is convenient to assume

$$n_e = \langle n_e \rangle + \bar{n}_e \sin \omega t, \quad (4)$$

$$T_e = \langle T_e \rangle + \bar{T}_e \sin(\omega t + \phi), \quad (5)$$

where ω is the frequency of the fluctuations, $\langle \rangle$ indicates a time average, ϕ is a possible phase difference between the density and temperature fluctuations, and $\bar{n}_e$ and $\bar{T}_e$ are the fluctuation amplitudes at the frequency ω (the subscripts ω for $\bar{n}_e$ and $\bar{T}_e$ are omitted for simplicity). For the microturbulence, ω is on the order of $2\pi \times 200 \text{ kHz}$, and $\bar{n}_e/n_e$ and $\bar{T}_e/T_e$ are on the order of 10^{-2} .^{6,7} The time dependent terms in Eqs. 4 and 5 represent a single Fourier component of the broadband fluctuations. In the experiment, it corresponds approximately to signal measured with a narrow bandpass filter. The broadband fluctuations can be described by integration of the Fourier components. Since $\bar{T}_e$ is assumed small, one can approximate C_{gj} by

$$C_{gj} = \bar{C}_{gj} + \bar{C}'_{gj} \bar{T}_e \sin(\omega t + \phi), \quad (6)$$

where $\bar{C}'_{gj}$ is a derivative of C_{gj} with respect to T_e , and $\bar{C}_{gj}$ and $\bar{C}'_{gj}$ are evaluated at $\langle T_e \rangle$. Substitutions of Eqs. 4 and 6 for n_e and C_{gj} in Eq. 3 yield

$$\frac{dP_j}{dt} = -A_{jg} P_j + \bar{C}_{gj} \langle n_e \rangle + \bar{C}_{gj} \bar{n}_e \sin \omega t + \bar{C}'_{gj} \langle n_e \rangle \bar{T}_e \sin(\omega t + \phi), \quad (7)$$

where the terms with $\frac{\bar{n}_e \bar{T}_e}{n_e T_e} \sim 10^{-4}$ have been neglected. A steady solution to Eq. 7 is

$$P_j = \langle P_j \rangle \left[1 + \frac{\bar{n}_e}{\langle n_e \rangle} \cos \psi \sin(\omega t - \psi) + \frac{\bar{T}_e}{\langle T_e \rangle} \left(\frac{\bar{C}'_{gj} \langle T_e \rangle}{\bar{C}_{gj}} \right) \cos \psi \sin(\omega t + \phi + \psi) \right], \quad (8)$$

where $\langle P_j \rangle = \frac{\bar{C}_{gj} \langle n_e \rangle}{A_{jg}}$ is the average level population, $\psi = \arctan\left(\frac{\omega}{A_{jg}}\right) \simeq 0$ since the radiative decay rate $1.428 \times 10^{10} \text{ /sec}$ is much larger than the fluctuation frequency $\omega/2\pi \sim 2 \times 10^5 \text{ /sec}$, therefore $\cos \psi \simeq 1$. The level population follows the fluctuations without any noticeable delay. Note also that those spectral lines originating from the forbidden transitions are too slow in their radiative decay rate (typically $< 10^3 \text{ /sec}$ or $\cos \psi \sim 0$) for their emission to follow the fluctuations. Thus, the forbidden lines, though emitting in visible or near ultraviolet range, are not applicable for this diagnostic.

The linear coefficient associated with $\frac{\bar{T}_e}{\langle T_e \rangle}$,

$$\Lambda_{gj} \equiv \frac{\bar{C}'_{gj} \langle T_e \rangle}{\bar{C}_{gj}}, \quad (9)$$

can be estimated as follows. The collisional excitation rate is

$$C_{gj} = \frac{8.010 \times 10^{-8} E_{gj}}{g_e T_e^{3/2}} \int_1^\infty dX \Omega_{gj}(X) \exp\left(-\frac{E_{gj} X}{T_e}\right), \quad (10)$$

where g_e is the degeneracy of the lower level of the transition, E_{gj} is the energy difference between the two levels, T_e and E_{gj} are in units eV, $X = \frac{E}{E_{gj}}$ is a normalized electron collision energy, and Ω_{gj} is the collision strength. Ω_{gj} can be accurately computed, which have been verified experimentally and discribed elsewhere.^{4,5,9-13} However, Ω_{gj} of the resonant transitions has a weak dependence on the X , thus can be approximated as a constant in the integration.⁴ This allows us to approximate the linear coefficient by

$$\Lambda_{gj} \simeq \frac{E_{gj}}{\langle T_e \rangle} - \frac{1}{2}. \quad (11)$$

Values for Λ_{gj} at ionization equilibrium temperature are listed in Table 1. It shows that magnitudes of Λ_{gj} are on the order of unity, while the linear coefficient for $\bar{n}_e$ is unity. Thus, two spectral lines are needed to decouple the $\bar{n}_e$ and $\bar{T}_e$ dependences. Another observation of Table 1 is that all of $\Delta n = 0$ transitions take values slightly larger then -0.5 because the energy gap E_{gj} between the lowly excited state and the ground state is much smaller than the ionization equilibrium temperature $\langle T_e \rangle$, and that all of $\Delta n = 1$ transitions take positive values about 0.5. Line intensity measurements for the transitions having similar dependences do not provide sensitive information to decouple $\bar{n}_e$ and $\bar{T}_e$. Therefore, the diagnostic needs to measure simultaneously the $\Delta n = 0$ and $\Delta n = 1$ spectral lines. Also note that the Λ_{gj} values of two spectral lines can be approximately the same, if the two lines have the same E_{gj} values and emit from the plasma of the same $\langle T_e \rangle$ temperature, according to Eq. 11. These lines, also being close to each other in wavelength,

can be considered as identical for having the same dependence on $\bar{n}_e$ and $\bar{T}_e$. Implications of this fact for instrumentation for the proposed diagnostic will be discussed in Sec. II.

In the above analysis, we neglected proton collisions. Proton collision effects were studied in previous publications for Li I-like to F I-like titanium and iron ions in tokamak plasma.^{4,10} Proton collisions significantly modify only the level population distribution of the ground configuration, and affect the upper level populations via the electron collisional excitation from the ground configuration. For the Be I-like and Li I-like ions which have a ground configuration of a single term, the proton collision contributes negligibly (less than 10^{-4} of the populations). For the B I-like and F I-like ions, it alternates the level populations by less than 7% which is still negligible for the diagnostic purpose. For the quartet states of N I-like ions, the proton collisions change the level population by less than 1%, and for the doublet states less than 17%. For the triplet states of the C I-like and O I-like ions, the proton collisions change the level populations by less than 10%. Substantial changes of $\sim 50\%$ in the level populations are found for the singlet states of the C I-like and O I-like ions by including the proton collision. The diagnostic should not use these lines strongly affected by the proton collision.

The ion density n_z can be considered as constant for this diagnostic. Previous studies showed that the characteristic time for the ionization equilibrium was on the order of milliseconds.^{1,3} An analysis for the relation between n_z and the microturbulence is given in Appendix I. It is important to note that the local emission of the spectral lines carry well localized information for $\bar{n}_e$ and $\bar{T}_e$. The impurity ions diffuse in the tokamak radial direction at a speed of about 10^3 cm/sec, and move along toroidal magnetic field lines at a speed of about 5×10^6 cm/sec. Because of the very high radiative rates for the resonant transitions, the excited ions will emit immediately where the collisions take place.

Summarizing the above discussion, the spectral line emissivity of Eq. 1 for the diag-

nostic can be written as

$$\epsilon_{gj} = \langle \epsilon_{gj} \rangle \left[1 + \frac{\tilde{n}_e}{\langle n_e \rangle} \sin \omega t + \Lambda_{gj} \frac{\tilde{T}_e}{\langle T_e \rangle} \sin(\omega t + \phi) \right], \quad (12)$$

where $\langle \epsilon_{gj} \rangle$ is an average of the emissivity.

II. Correlations of spectral line intensities

To make localized measurements of $\tilde{n}_e$ and $\tilde{T}_e$, two pairs of monochromators are set with lines of sight nearly perpendicular to each other and crossing at a small common volume, as shown in Fig. 1. Each pair of monochromators measure two spectral lines of $\Delta n = 0$ and $\Delta n = 1$ transitions, respectively. The diagnostic employs monochromators of low spectral resolution. As discussed in the last section, if the spectral lines are chosen from Table 1, close to each other in wavelength and emitted from the same plasma volume, they can be considered as identical for having the same $\tilde{n}_e$ and $\tilde{T}_e$ dependences, regardless of what ions they are emitted from. Thus, the intensities of these lines can be added. For instance, it is unnecessary to separate the Ti XIX 169.6 Å line from the Ti XVI 169.8 Å line in the measurement. In fact, addition of the two blended lines will increase the signal-to-noise ratio of the measurement as will be discussed later. Those spectral lines which largely depend on two steps of electron collisional excitations via other highly excited levels are too small (a factor of hundreds weaker than the chosen lines) to disturb the measurement. Spectral lines of low Z ions, such as O V 173 Å, are emitted from the edge plasma,¹⁴ and can be largely eliminated by intensity correlations discussed in the following paragraphs. The spectral resolution should be chosen to avoid those strong spectral emissions from the common plasma volume of which the emissivities are significantly affected by atomic processes other than the electron collision. To measure the Ti XIX 169.6 Å line, a spectral resolution of 10 Å will be sufficient to cut off the singlet lines of C I-like titanium. Thus, the scheme of using monochromators of low spectral resolution is justified.

With the system illustrated in Fig. 1, we will simultaneously obtain four spectral line

intensities, (abbreviating $\langle n_a \rangle$ as n_a , $\langle T_a \rangle$ as T_a , and $\langle \epsilon \rangle$ as ϵ),

$$I_{ab} = N_{ab} + \xi_{ab} \epsilon_a \left(\frac{\tilde{n}_a}{n_a} + \Lambda_a \frac{\tilde{T}_a}{T_a} \right), \quad (13)$$

where subscript a will be 0 for $\Delta n = 0$ transition and 1 for $\Delta n = 1$ transition, subscript b will be v to indicate the vertical viewing direction and h to indicate the horizontal viewing direction. I_{ab} are in units of photoevents per data-point. ϵ_a are the averaged emissivities of the spectral sources in the common volume, and are obtained by a spatial inversion of measured radial profiles of intensity I_{ah} and I_{av} .³ Both $\tilde{n}_a$ and $\tilde{T}_a$ are implicitly time-dependent functions of the microturbulent fluctuations in the common volume rather than the amplitudes as in Eqs. 4-12. ξ_{ab} are the instrumental constants relating the photo-events and the emissivity. N_{ab} are the number of photoevents per data-point integrated along the lines of sight, excluding the intensity fluctuations originating from the common volume. Bandpass filters at the high frequency will be used to cut off the low frequency fluctuations in the photo-electron current of the monochromators. After the filtering, the second term in Eq. 13 will be retained as the high frequency fluctuation of the spectral intensity due to $\tilde{n}_a$ and $\tilde{T}_a$ in the common volume, and I_{ab} and N_{ab} will be reduced to $\tilde{I}_{ab}$ and $\tilde{N}_{ab}$ corresponding to the high frequency fluctuations in the integrated spectral intensities, respectively. It is important to be aware of the fact that N_{ih} and N_{jv} can be correlated when magnetohydrodynamic (MHD) modes are active. However, the frequency of MHD modes are at several kilohertz, which are much lower than that of the microturbulence fluctuations of interest. After the filtering, the MHD signals will thus be eliminated as well as other slow variations such as the change in the ion density. Because $\tilde{N}_{ih}$ and $\tilde{N}_{jv}$ are related to the microturbulent fluctuations with the relatively shorter correlation length, and they are integrated in the separated lines of sight, we can assume that $\tilde{N}_{ih}$ and $\tilde{N}_{jv}$ are uncorrelated. A precise definition for the common volume and a method for measuring the correlation length of the fluctuation will be discussed later.

The four $\tilde{I}_{ab}$ can form four linear correlations between the vertical and the horizontal

measurements,

$$\begin{aligned} \langle \tilde{I}_{iv} \tilde{I}_{jh} \rangle = & \langle \tilde{N}_{iv} \tilde{N}_{jh} \rangle + \langle \tilde{N}_{iv} \xi_{jh} \epsilon_j \left(\frac{\tilde{n}_e}{n_e} + \Lambda_j \frac{\tilde{T}_e}{T_e} \right) \rangle + \langle \tilde{N}_{jh} \xi_{iv} \epsilon_i \left(\frac{\tilde{n}_e}{n_e} + \Lambda_i \frac{\tilde{T}_e}{T_e} \right) \rangle \\ & + \xi_{iv} \xi_{jh} \epsilon_i \epsilon_j \left[\left\langle \left(\frac{\tilde{n}_e}{n_e} \right)^2 \right\rangle + \Lambda_i \Lambda_j \left\langle \left(\frac{\tilde{T}_e}{T_e} \right)^2 \right\rangle + (\Lambda_i + \Lambda_j) \left\langle \frac{\tilde{n}_e}{n_e} \frac{\tilde{T}_e}{T_e} \right\rangle \right], \end{aligned} \quad (14)$$

where $\langle \rangle$ indicates an average of sufficient data points over a period which will be determined later. In the above equation, any correlations with $\tilde{N}_{ab}$'s are ideally zero. The correlation coefficients are defined as

$$r_{ij} \equiv \frac{\langle \tilde{I}_{iv} \tilde{I}_{jh} \rangle}{\xi_{iv} \xi_{jh} \epsilon_i \epsilon_j} = \left\langle \left(\frac{\tilde{n}_e}{n_e} \right)^2 \right\rangle + \Lambda_i \Lambda_j \left\langle \left(\frac{\tilde{T}_e}{T_e} \right)^2 \right\rangle + (\Lambda_i + \Lambda_j) \left\langle \frac{\tilde{n}_e}{n_e} \frac{\tilde{T}_e}{T_e} \right\rangle. \quad (15)$$

In Eqs. 15, r_{ij} can be calculated from the measured quantities, and Λ_i and Λ_j can be found from Table 1. Solving Eqs. 15, we obtain the fluctuation measurements,

$$\begin{aligned} \left\langle \left(\frac{\tilde{T}_e}{T_e} \right)^2 \right\rangle &= \frac{r_{00} + r_{11} - 2r_{01}}{(\Lambda_0 - \Lambda_1)^2}, \\ \left\langle \left(\frac{\tilde{n}_e}{n_e} \right)^2 \right\rangle &= \frac{r_{00} \Lambda_1^2 + r_{11} \Lambda_0^2 - 2r_{01} \Lambda_0 \Lambda_1}{(\Lambda_0 - \Lambda_1)^2}, \\ \left\langle \frac{\tilde{n}_e}{n_e} \frac{\tilde{T}_e}{T_e} \right\rangle &= \frac{r_{01}(\Lambda_0 + \Lambda_1) - r_{00} \Lambda_1 - r_{11} \Lambda_0}{(\Lambda_0 - \Lambda_1)^2}. \end{aligned} \quad (16)$$

The measured $\tilde{n}_e$ and $\tilde{T}_e$ in Eqs. 16 are the localized quantities as defined for Eqs. 13. However, localization of the diagnostic, using the correlation technique, is limited to the dimension of the correlation length of the fluctuation.^{6,7} The actual common volume where the fluctuations are measured should be extended to the view-crossing volume's vicinities where the correlation between the vertically and the horizontally measured signals is nonzero. In general, regardless which type of diagnostic technique is used,¹⁵⁻¹⁷ a directly measured value of the fluctuation is defined with a volume of the diagnostic's spatial resolution. It is a function of $\tilde{f}_r$ and $\frac{\ell_c}{\ell_o}$, where $\tilde{f}_r$ is the fluctuation defined in a macroscopically small, but microscopically large, volume element, ℓ_c is the correlation length and ℓ_o is the dimension of the observed volume. By changing ℓ_o , one will find

different values of the fluctuations for integrating the fluctuations in volumes of different sizes. One also can theoretically derive the function by statistical analysis. Thus, $\tilde{f}_r$ and ℓ_c can be determined from measurements of the fluctuations in two volumes different in size. Details for the derivation of $\tilde{f}_r$ and ℓ_c are beyond the scope of this paper.

The next question is how accurate the measurement can be and how long the signals have to be integrated. The step from Eqs. 14 to Eqs. 15 was based on an ensemble of an infinite amount of data points for the correlation. In reality, the experimental data ensemble is finite. Thus, the correlation of two random signals, $\langle \tilde{N}_{iv} \tilde{N}_{jh} \rangle$, will not be exactly zero. According to the statistics theory as presented in Appendix II,^{18,19} the standard deviation of the correlation for the uncorrelated signals is

$$\Delta \langle \tilde{N}_{iv} \tilde{N}_{jh} \rangle = \frac{\sqrt{\langle \tilde{N}_{iv}^2 \rangle \langle \tilde{N}_{jh}^2 \rangle}}{\sqrt{2(N-1)}} , \quad (17)$$

where N is the number of data-points in one sample. This non-zero standard deviation is a dominant noise source. The cross terms between $\tilde{N}_{ab}$ and the fluctuations in the common volume can be ignored since the emission from the common volume is much smaller than the integrated signals. Background radiation, scattered light, and electronic noise were not written explicitly in the above equations. However, they are much smaller than the chosen spectral lines of the strong resonant transitions. To determine $\langle \tilde{N}_{iv}^2 \rangle$ and $\langle \tilde{N}_{jh}^2 \rangle$, we assume that the number of photoevents in each data-point is random and that it follows a Poisson distribution. The intensity fluctuation outside the common volume can also be related to $\tilde{n}_e$ and $\tilde{T}_e$. As the noise source, the intensity fluctuation due to $\tilde{n}_e$ and $\tilde{T}_e$ outside the common volume is however much less significant than the statistical fluctuation of the photon emission as shown in Appendix II. Eventhough $\frac{\tilde{n}_e}{n_e}$ and $\frac{\tilde{T}_e}{T_e}$ in the edge plasma region take larger values than in the center, they contribute negligibly in $\tilde{N}_{ab}$ because the spectral line emissions are near zero at the plasma edge. Thus, we have approximately $\langle \tilde{N}_{iv}^2 \rangle = \langle \tilde{N}_{jh}^2 \rangle = N_i$, assuming the same average photon counts N_i for the same spectral

line measured in the different directions. The noise level in $\langle \bar{I}_{iv} \bar{I}_{jh} \rangle$ is approximately

$$\Delta \langle \bar{I}_{iv} \bar{I}_{jh} \rangle = \sqrt{\frac{N_i N_j}{2(N-1)}}. \quad (18)$$

Let us assume that we will observe a cubic plasma volume of dimension ℓ at the tokamak center, and that the radial emissivity profile of the XUV spectral lines is $\epsilon_i(\rho) = \epsilon_i \exp(-(\rho/\rho_0)^2)$, where ρ is the tokamak minor radius, and ρ_0 is a characteristic radius of the emission shell. Thus, the spectral line brightness through the center is $B_i = \sqrt{\pi} \rho_0 \epsilon_i$. The instrumental constant in Eqs. 13 is $\xi_i = \zeta_i \ell^3 \Delta\Omega \Delta t$, where ζ_i is the photo-efficiency, $\Delta\Omega$ is the emission solid angle for the observation, and Δt is the integration time for one data point. The number of photo-events in one data point is $N_i = B_i \xi_i / \ell$. The time to collect N data points is $\tau = N \Delta t$. With the above relations and notations, the signal-to-noise ratio for r_{ij} is

$$\eta_{ij} \equiv \frac{r_{ij}}{\Delta r_{ij}} = \frac{\langle \bar{I}_{iv} \bar{I}_{jh} \rangle}{\Delta \langle \bar{I}_{iv} \bar{I}_{jh} \rangle} = \frac{\sqrt{2} \ell^4 \Delta\Omega \sqrt{\zeta_i B_i \zeta_j B_j} \sqrt{\tau \Delta t} r_{ij}}{\pi \rho_0^2}. \quad (19)$$

When $\eta_{ij} = 1$, the signal level r_{ij} is equal to the noise level Δr_{ij} which is defined as the measurement accuracy of r_{ij} . Let us consider an ideal experiment to estimate the accuracy by using Eq. 19 with $\eta_{ij} = 1$. Let us require the spatial resolution of ($\ell =$) 1 cm, the integration time for one data point $\Delta t = 10^{-6}$ sec to measure high frequency fluctuations, and the integration time of $\tau = 10$ msec to measure transient plasma conditions. Other conditions are limited by access to a medium size tokamak and by the available XUV optics. We assume that concave LSM mirrors of 5 cm in diameter will be installed 50 cm away from the tokamak center to collect light. The LSM mirrors will work as a bandpass-reflective filter, and form images of the common plasma volume on photo-detectors. The photo efficiency of the monochromators is $\zeta = 0.06$. The radii of the emission shells were found to be ($\rho_0 \simeq$) 10 cm, and the line brightnesses of the $\Delta n = 0$ transitions of the tokamak intrinsic impurities were on the order of 10^{15} photons/cm² · sr · sec.⁴ There are no experimental values available for the line brightness of the $\Delta n = 1$ transitions. With the distorted-wave approximation, including nine configurations for the Ti XIX ion, we found that the

line intensity ratio of the $\Delta n = 0$ transitions to the $\Delta n = 1$ transition is ~ 5 .²⁰ With these conditions, the accuracy for r_{00} will be 4.7×10^{-6} , and the accuracy for r_{11} will be 2.4×10^{-5} . The accuracy for the derived $\langle(\bar{T}_e/T_e)^2\rangle$, $\langle(\bar{n}_e/n_e)^2\rangle$ and $\langle(\bar{T}_e/T_e)(\bar{n}_e/n_e)\rangle$ will be on the same order as for r_{11} , since $\Lambda_0 - \Lambda_1 \simeq 1$ in the Eqs. 16 when using both $\Delta n = 0$ and $\Delta n = 1$ transitions. Thus, the noise level in the derived $\sqrt{\langle(\bar{T}_e/T_e)^2\rangle}$, $\sqrt{\langle(\bar{n}_e/n_e)^2\rangle}$ and $\sqrt{\langle(\bar{T}_e/T_e)(\bar{n}_e/n_e)\rangle}$ will be about 5×10^{-3} with integration time of $\tau = 10 \text{ msec}$. Since the measured line intensity will be increased by including blended spectral lines with the low spectral resolution monochromators, the theoretical accuracy of the diagnostic can be higher than the above estimate. Note that we can get a much faster integration time τ rather than improving the accuracy slightly, according to Eq. 19. For instance, the Ti XIX 169.6 Å line of intrinsic tokamak impurity can be as bright as $3.5 \times 10^{15} \text{ photons/sr} \cdot \text{cm}^2 \cdot \text{sec}$ according to our previous measurement;⁵ this stronger intensity can result in an accuracy of 2.6×10^{-3} with $\tau = 10 \text{ msec}$ if we want higher accuracy; when the accuracy of 5×10^{-3} is sufficient, this stronger intensity can reduce the integration time τ to be 0.8 msec.

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Table I. XUV Spectral Lines of $\Delta n = 0$ and $\Delta n = 1$ resonant transitions
for the $\bar{n}_e$ and $\bar{T}_e$ study^a

Transitions	Titanium			Iron		
	$\lambda(\text{\AA})$	$E(\text{eV})$	Λ	$\lambda(\text{\AA})$	$E(\text{eV})$	Λ
Li I-like $T_{Eq}(\text{eV}) :$	831			1616		
$2s\ ^2S_{1/2} - 2p\ ^2P_{1/2}$	309.1	40	-0.45	255.1	49	-0.47
$2s\ ^2S_{1/2} - 2p\ ^2P_{3/2}$	259.3	48	-0.44	192.0	65	-0.46
$2s\ ^2S_{1/2} - 3p\ ^2P$	15.2	814	0.48	10.6	1170	0.22
Be I-like $T_{Eq}(\text{eV}) :$	703			1291		
$2s^2\ ^1S_0 - 2s2p\ ^1P_1$	169.6	73	-0.40	132.9	47	-0.46
$2s2p\ ^1P - 2s3d\ ^1D$	17.1	799	0.64	11.7	1150	0.39
$2s2p\ ^3F - 2s3d\ ^3D$	16.5	769	0.59	11.3	1097	0.35
B I-like $T_{Eq}(\text{eV}) :$	619			1138		
$2s^22p\ ^2P_{3/2} - 2s2p^2\ ^2D_{5/2}$	197.7	63	-0.40	155.9	80	-0.43
$2s^22p\ ^2P_{1/2} - 2s2p^2\ ^2D_{3/2}$	179.9	69	-0.39	135.8	90	-0.42
$2s^22p\ ^2P_{1/2} - 2s2p^2\ ^2S_{1/2}$	148.4	84	-0.36	117.2	105	-0.41
$2s^22p\ ^2P_{3/2} - 2s2p^2\ ^2P_{1/2}$	147.6	84	-0.36	116.3	108	-0.40
$2s^22p\ ^2P_{3/2} - 2s2p^2\ ^2P_{3/2}$	144.7	86	-0.36	114.4	110	-0.40
$2s^22p\ ^2P - 2s^23d\ ^2D$	17.3	717	0.66	11.9	1042	0.42
$2s^22p\ ^2P - 2s2p(^3P^0)3p\ ^2P$	16.9	747	0.71	11.7	1060	0.43
$2s^22p\ ^2P - 2s2p(^3P^0)3p\ ^2D$	16.6	747	0.71	11.4	1090	0.46
C I-like $T_{Eq}(\text{eV}) :$	545			1000		
$2s^22p^2\ ^3P_2 - 2s2p^3\ ^3D_3$	179.9	69	-0.39	145.7	85	-0.42
$2s^22p^2\ ^3P_1 - 2s2p^3\ ^3D_2$	175.2	71	-0.39	142.2	87	-0.41
$2s^22p^2\ ^3P_0 - 2s2p^3\ ^3D_1$	166.2	74	-0.38	128.7	96	-0.40
$2s^22p^2\ ^3P_2 - 2s2p^3\ ^3P_1$	160.6	81	-0.37	123.8	105	-0.40
$2s^22p^2\ ^3P_2 - 2s2p^3\ ^3P_2$	158.5	78	-0.37	121.2	102	-0.40

$2s^2 2p^2 \ ^3P_1 - 2s 2p^3 \ ^3P_0$	154.9	80	-0.37	118.7	104	-0.40
$2s^2 2p^2 \ ^3P_1 - 2s 2p^3 \ ^3P_1$	154.1	81	-0.37	117.5	105	-0.40
$2s^2 2p^2 \ ^3P_0 - 2s 2p^3 \ ^3P_1$	147.4	81	-0.37	108.1	105	-0.40
$^b 2s^2 2p^2 \ ^1D_2 - 2s 2p^3 \ ^1D_2$	141.9	87	-0.36	113.3	109	-0.39
$2s^2 2p^2 \ ^3P_2 - 2s 2p^3 \ ^3S_1$	127.8	99	-0.34	102.2	124	-0.38
$^b 2s^2 2p^2 \ ^1D_2 - 2s 2p^3 \ ^1P_1$	124.5	96	-0.34	98.4	121	-0.38
$2s^2 2p^2 \ ^3P_1 - 2s 2p^3 \ ^3S_1$	123.7	99	-0.34	97.9	125	-0.38
$2s^2 2p^2 \ ^3P_0 - 2s 2p^3 \ ^3S_1$	119.3	99	-0.34	91.3	125	-0.38
$2s^2 2p^2 \ ^3P - 2s^2 2p 3s \ ^3P$	19.5	636	0.53			
$^b 2s^2 2p^2 \ ^1D - 2s^2 2p 3d \ ^1F$	18.3	677	0.59	12.4	1000	0.50
$2s^2 2p^2 \ ^3P - 2s^2 2p 3d \ ^3D$	18.2	681	0.60			
$2s^2 2p^2 \ ^3P - 2s^2 2p 3d \ ^3P$	18.1	685	0.61	12.3	1008	0.51
N I-like $T_{Eq}(eV) :$	469			894		
$2s^2 2p^3 \ ^4S_{3/2} - 2s 2p^4 \ ^4P_{5/2}$	169.8	73	-0.34	132.9	93	-0.40
$2s^2 2p^3 \ ^4S_{3/2} - 2s 2p^4 \ ^4P_{3/2}$	161.2	77	-0.34	121.8	102	-0.39
$2s^2 2p^3 \ ^4S_{3/2} - 2s 2p^4 \ ^4P_{1/2}$	157.8	79	-0.33	118.7	104	-0.38
$2s^2 2p^3 \ ^2D_{5/2} - 2s 2p^4 \ ^2D_{5/2}$	145.7	83	-0.32	113.3	107	-0.38
$2s^2 2p^3 \ ^2D_{3/2} - 2s 2p^4 \ ^2D_{3/2}$	143.5	85	-0.32	110.6	110	-0.38
$2s^2 2p^3 \ ^2D_{5/2} - 2s 2p^3 (^3P) 3d \ ^2F$	19.6	633	0.85	13.1	946	0.56
$2s^2 2p^3 \ ^2D_{5/2} - 2s 2p^3 (^3P) 3d \ ^2D$	19.4	639	0.86	13.1	946	0.56
$2s^2 2p^3 \ ^2D_{5/2} - 2s 2p^3 (^1D) 3d \ ^2F$	19.2	646	0.88			
$2s^2 2p^3 \ ^4S_{3/2} - 2s 2p^3 (^3P) 3d \ ^4P$	19.1	649	0.88	13.7	905	0.51
O I-like $T_{Eq}(eV) :$	408			799		
$2s^2 2p^4 \ ^3P_1 - 2s 2p^5 \ ^3P_2$	148.6	87	-0.29	120.0	108	-0.36
$2s^2 2p^4 \ ^3P_0 - 2s 2p^5 \ ^3P_1$	142.8	90	-0.28	110.0	117	-0.35
$2s^2 2p^4 \ ^3P_1 - 2s 2p^5 \ ^3P_1$	142.1	90	-0.28	111.7	117	-0.35
$2s^2 2p^4 \ ^3P_2 - 2s 2p^5 \ ^3P_2$	140.4	87	-0.29	108.4	108	-0.36

$2s^2 2p^4 \ ^3P_1 - 2s^2 2p^5 \ ^3F_0$	138.9	90	-0.28	106.3	118	-0.35
$2s^2 2p^4 \ ^3P_2 - 2s^2 2p^5 \ ^3P_1$	134.6	90	-0.28	101.6	117	-0.35
$^b 2s^2 2p^4 \ ^1D_2 - 2s^2 2p^5 \ ^1P_1$	124.5	96	-0.26	91.0	131	-0.34
$2s^2 2p^4 \ ^3P - 2s^2 2p^3(^4S)3s \ ^3S$	23.1	536	0.81	15.0	823	0.53
$2s^2 2p^4 \ ^3P - 2s^2 2p^3(^2D)3s \ ^3D$	22.5	551	0.85	14.9	832	0.54
$^b 2s^2 2p^4 \ ^1D - 2s^2 2p^3(^2D)3d \ ^1D$	20.8	596	0.96	13.9	892	0.62
$2s^2 2p^4 \ ^3P - 2s^2 2p^3(^2D)3d \ ^3D$	20.5	604	0.98	13.5	918	0.65
$2s^2 2p^4 \ ^3P - 2s^2 2p^3(^2D)3d \ ^3S$	20.3	611	1.00	13.5	918	0.65
$2s^2 2p^4 \ ^3P - 2s^2 2p^3(^2P)3d \ ^3P$	20.2	614	1.00			
$2s^2 2p^4 \ ^3P - 2s^2 2p^3(^2P)3d \ ^3D$	20.1	617	1.01	13.4	925	0.66
F I-like $T_{Eq}(eV) :$	331			660		
$2s^2 2p^5 \ ^2P_{1/2} - 2s^2 2p^6 \ ^2S_{1/2}$	129.4	100	-0.20	102.6	126	-0.31
$2s^2 2p^5 \ ^2P_{3/2} - 2s^2 2p^6 \ ^2S_{1/2}$	122.0	100	-0.20	93.9	126	-0.31
$2s^2 2p^5 \ ^2P - 2s^2 2p^4(^3P)3s \ ^4P$	25.0	496	1.00	16.1	770	0.67
$2s^2 2p^5 \ ^2P - 2s^2 2p^4(^1S)3s \ ^2S$	23.7	523	1.08	15.5	800	0.71
$2s^2 2p^5 \ ^2P - 2s^2 2p^4(^1D)3d \ ^2D$	21.8	569	1.22	14.2	873	0.82
$2s^2 2p^5 \ ^2P - 2s^2 2p^4(^1S)3d \ ^2D$	21.4	579	1.25	14.0	886	0.84

^a The wavelength and the line identity are taken from Ref. 10 and 11. The ionization equilibrium temperature T_{Eq} is taken from Ref. 18. E is the averaged energy gap weighted by the electron-collisional excitation rates. Λ is defined by Eq. 9, approximated by Eq. 11, and calculated at T_{Eq} .

^b These lines may not be suitable for the diagnostic of $\bar{n}_e$ and $\bar{T}_e$ because of strong proton collision effects which are discussed in Section II.

Appendix I.a

Relation between n_z and microturbulence

With the fluctuations in the plasma, the ionization process is described by³

$$\frac{dn_z}{dt} = -n_e(n_z Q_z + n_z R_z - n_{z-1} Q_{z-1} - n_{z+1} R_{z+1}), \quad (A1)$$

where Q_s and R_s are total ionization and recombination rates for an s charge state, respectively. Here, we did not include the diffusion in Eqs. A1 since the diffusion speed is on the order of 1 cm/msec while we are interested in the high frequency fluctuations. With the zero order approximation of $\frac{dn_z}{dt} = 0$, Eqs. A1 are reduced to equations for the ionization equilibrium. n_z in the equilibrium is a function of T_e , and is independent of n_e . Perturbing n_z near the equilibrium, expanding both Q_s and R_s as linear functions of $\bar{T}_e$, and keeping only the linear terms of $\bar{n}_e$ and $\bar{T}_e$ in the solution, we found

$$n_z = \langle n_z \rangle \left[1 + \frac{\alpha \frac{\bar{T}_e}{\langle T_e \rangle} \sin(\omega t + \psi_z)}{\sqrt{1 + (\omega/\omega_z)^2}} \right], \quad (A2)$$

where $\omega_z = \langle n_e \rangle (\bar{Q}_z + \bar{R}_z)$, $\psi_z = \arctan(\omega/\omega_z)$,

$$\alpha = \frac{\langle T_e \rangle [\bar{R}_z (\bar{Q}'_{z-1}/\bar{Q}_{z-1} - \bar{R}'_z/\bar{R}_z) + \bar{Q}_z (\bar{R}'_{z+1}/\bar{R}_{z+1} - \bar{Q}'_z/\bar{Q}_z)]}{\bar{Q}_z + \bar{R}_z},$$

the superscript / represent derivatives with respect to T_e , and $\bar{Q}$ and $\bar{R}$ take values at $\langle T_e \rangle$. Determined by the ionization equilibrium equations, $\langle n_z \rangle$ is an average of the ion density and independent of n_e . Magnitudes of α for the listed ions in Table 1 are about unity. ω_z for Ti XIX in the tokamak plasma is about 500 /sec. Since $\omega \gg \omega_z$ when we measure the high frequency fluctuation, n_z can be treated as constant according to Eq. A2.

Appendix I.b

Correlation of uncorrelated signals

According to the statistics theory, a normalized linear correlation of two random samples of X and Y , defined as

$$r = \frac{\langle \tilde{X} \tilde{Y} \rangle}{\sqrt{\langle \tilde{X}^2 \rangle \langle \tilde{Y}^2 \rangle}}, \quad (A3)$$

may lead to a non-zero value of r with a probability^{18,19}

$$P(r, \nu) = \frac{1}{\sqrt{\pi}} \frac{\Gamma[(\nu + 1)/2]}{\Gamma(\nu/2)} (1 - r^2)^{(\nu-2)/2}, \quad (A4)$$

where $\nu = N - 2$ is the number of degrees of freedom for the samples of N data points, and Γ is the gamma function. The square of the standard deviation for r is

$$\langle \tilde{r}^2 \rangle = \int_{-1}^1 P(r, \nu) r^2 dr = \frac{1}{2(\nu + 1)}. \quad (A5)$$

The standard deviation of the correlation is

$$\Delta \langle \tilde{X} \tilde{Y} \rangle = \frac{\sqrt{\langle \tilde{X}^2 \rangle \langle \tilde{Y}^2 \rangle}}{\sqrt{2(N - 1)}}. \quad (A6)$$

This standard deviation is applicable as the noise level produced by the linear correlation of uncorrelated signals in Eqs. 16. The square of standard deviation for the random counts of a Poisson distribution is $\langle \tilde{N}_{iv}^2 \rangle = \langle \tilde{N}_{ih}^2 \rangle = N_i$, assuming the same average photon counts N_i for the same spectral line measured in the different directions.

The values of $\tilde{N}_{iv}$ and $\tilde{N}_{jh}$ are also related to $\frac{\tilde{n}_e}{n_e}$ and $\frac{\tilde{T}_e}{T_e}$ along the lines of sight. To estimate this effect, we assume the following model,

$$\epsilon = \epsilon_0 \left(1 + \tilde{\sigma}_a \frac{e^{k(\rho/a)^2}}{e^k} \right) e^{-(\rho/\rho_0)^2}, \quad (A7)$$

where $\tilde{\sigma}_a$ is a sum of $\frac{\tilde{n}_e}{n_e}$ and $\frac{\tilde{T}_e}{T_e}$ at the plasma edge, a is the minor radius of the tokamak plasma, ρ is the radius, ϵ_0 is the emissivity at the plasma center, ρ_0 is the radius of the

emission shell, and k is a constant to be given. At $\rho = 0$, the sum of $\frac{\tilde{n}_e}{\tilde{n}_e}$ and $\frac{\tilde{T}_e}{\tilde{T}_e}$ in the model is $\tilde{\sigma}_a/e^k$. Assuming $k = (a/\rho_0)^2$, we will have a constant emissivity fluctuation along the lines of sight. If $k = 4$, $\tilde{\sigma}_a/e^k$ at $\rho = 0$ is lower than the expected fluctuations at the center,^{6,7} and $\rho_0 = a/2$ is larger than the radius of the observed emission shells. Thus, we are giving a lower limit of the estimated signal-to-noise ratio related to $\tilde{n}_e$ and $\tilde{T}_e$,

$$\frac{\langle \tilde{I}_{iv} \tilde{I}_{jh} \rangle}{\Delta \langle \tilde{I}_{iv} \tilde{I}_{jh} \rangle} = \frac{\ell^2 \sqrt{2(N-1)}}{2a\delta\ell}, \quad (A8)$$

for the measurement at the plasma center, where ℓ is the spatial resolution and $\delta\ell$ is the correlation length of the fluctuations. Eq. A8 shows that the signal-to-noise ratio related to $\frac{\tilde{n}_e}{\tilde{n}_e}$ and $\frac{\tilde{T}_e}{\tilde{T}_e}$ is not related to the spectral line intensity, and that it can be improved by increasing the number of data-points in one sample. Assuming $\delta\ell = \ell = 1$ cm and $2a = 50$ cm, we find that we need 1251 data-points in one sample to measure a fluctuation of $\tilde{\sigma}_a/e^4$ at the plasma center, or that $\tau \simeq 1.25$ ms (for $\Delta t = 1\mu\text{m}$ in Sec. II) is a maximum integration time for the accuracy. This needed integration time is much less than $\tau \simeq 10$ ms for eliminating the Poisson-distributed random fluctuations which is considered in Sec. II.

V. Principal Investigator's Research Experience and Recent Publications

Warren Moos received the Ph.D. degree from the University of Michigan in 1962. He subsequently held positions at Stanford University and the Johns Hopkins University, where he is presently Professor of Physics and Astronomy and Director of the Center for Astrophysical Sciences. Dr. Moos has done extensive research in quantum electronics, solid state physics, atomic physics, space physics, plasma physics and the design of novel spectroscopic instrumentation. He is a Fellow of the American Physical Society and a member of the American Astronomical Society. A list of publications for the past five years is attached.

Publications of W. Moos (past five years)

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VI. Current and Pending Support for the Research Project

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The project that this proposal concerns is not presently nor has been in the past supported by any source other than OER; and this proposal is not being submitted to any other possible sponsors.

OTHER CURRENT RESEARCH PROJECTS OF PRINCIPAL INVESTIGATOR, W. MOOS

Title	Agency	Capacity
Rocket and Laboratory Experiments in Astronomy	NASA	Co-Investigator
The Hopkins Ultraviolet Telescope	NASA	Co-Investigator
Studies of the Ultraviolet Spectra of Astronomical Sources	NASA	Principal Investigator
Optical Studies of Potential Spectroscopic Instruments for the FUSE	NASA	Principal Investigator
Lyman, The Far Ultraviolet Spectroscopic Explorer	NASA	Principal Investigator
Space Telescope Imaging Spectrograph	NASA	Principal Investigator

VII. Recent Publications Reporting Project Results

D. Wroblewski, L.K. Huang, H.W. Moos and P.E. Phillips, Spectroscopic Measurement of the Poloidal Field Profile in the Texas Experimental Tokamak, Review of Scientific Instruments, **59**, 1632 (1988).

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