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On the harmonic technique to measure electron temperature with high time resolution

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A detailed study of the harmonic technique, which exploits the generation of harmonics resulting from excitation of the nonlinearity of the single Langmuir probe characteristic, is presented. The technique is used to measure electron temperature and its fluctuations in tokamak plasmas and the technical issues relevant to extending the technique to high bandwidth (200 kHz) are discussed. The technique has been implemented in a fast reciprocating probe in the TEXTOR tokamak, gaining the ability to study denser and hotter plasmas than previously possible. A corrected analytical expression is derived for the harmonic currents. Measurement of the probe current by inductive pickup is introduced to improve electrical isolation and bandwidth. The temperature profiles in the boundary plasma of TEXTOR have been measured with high spatial (~2 mm) and temporal (200 kHz) resolution and compared to those obtained with a double probe. The exact expansion of the probe characteristic in terms of Bessel functions is compared to a computationally efficient power series. Various aspects of the interpretation of the measurement are discussed such as the influence of plasma potential and density fluctuations. The technique is well suited to study fast phenomena such as transient plasma discharges or turbulence and turbulent transport in plasmas. © 1999 American Institute of Physics.

I. INTRODUCTION

Langmuir probes are successfully used in many plasma devices1–5 such as plasma reactors, linear machines, and fusion experiments, providing measurements of electron temperature, density, and other parameters. In fusion devices, such as tokamaks, turbulence is found to be responsible for a considerable part of the energy and particle losses in the boundary plasma.6–11 Turbulent particle transport studies are routinely performed using multi-pin probe configurations11–13 and the different pins are used for simultaneous measurements of fluctuating floating potential \( \tilde{V}_f \) poloidal and radial electric fields \( \tilde{E}_\theta, \tilde{E}_r \), the local plasma density \( n \), and its fluctuations \( \tilde{n} \). The evaluation of turbulence-driven radial particle transport \( \tilde{\Gamma}_r \) is possible by cross correlating the fluctuating quantities. Electron temperature fluctuations \( \tilde{T}_e \) enter the particle flux calculations through the electric field inferred from the difference of floating potentials at spaced probe pins14 and from the evaluation of density fluctuations from saturation current fluctuations

\[
\tilde{\Gamma}_r = \langle \tilde{n} \tilde{E}_\phi \rangle / B_\phi, \quad \tilde{E}_\phi = -\nabla_\phi \tilde{V}_s = -\nabla_\phi (\tilde{V}_f + 3.5k \tilde{T}_e),
\]

\[
\frac{\tilde{n}}{\langle n \rangle} = \frac{\tilde{I}_{sat}}{\langle I_{sat} \rangle} \frac{1}{2} \frac{\tilde{T}_e}{\langle T_e \rangle}.
\]

The contribution of \( \tilde{T}_e \) on such calculations is often neglected under the assumption, based on limited experimental results,12,14 that \( \tilde{T}_e/T_e \leq 15\% \) in the edge and that the phase between \( \tilde{E}_\phi \) and \( \tilde{E}_r \) is \( \pi \), corresponding to a strong correlation. Reports12,15,16 of higher levels of temperature fluctuations may bring a certain part of conventional evaluation of particle transport under question. It has been noted17 that the contribution of temperature fluctuations to the cross-field fluctuations...
heat transport cannot be neglected in many cases, thus a reliable database for both \( T_e \) and its poloidal correlation lengths is needed. The cross-field heat transport can be expressed as the sum of convective and conductive terms

\[
\bar{Q}_{\text{tot}} = \bar{Q}_{\text{cond}} + \bar{Q}_{\text{conv}} = \frac{5}{2} \frac{\langle T_e E_B \rangle}{B_0} + \frac{5}{2} \Gamma, T_e.
\]

A requirement of these measurements, which may not be met by all diagnostic systems, is that all the fluctuating quantities are measured within a correlation length (poloidal, radial, and toroidal), i.e., that the plasma sampled by the various tips is the same. The probe diagnostic techniques used so far do not necessarily meet the requirements of locality, especially in turbulent conditions. Among the techniques used for these measurements is the triple probe technique. This technique, which is otherwise straightforward, is challenged by the need to sample a small plasma volume with three tips and maintain very accurate tip geometry, especially for high time resolution measurements of turbulent plasmas. The fast-sweep single probe technique presents challenges because the probe characteristics are affected by fluctuating electric fields, resulting in apparent temperature fluctuations, requiring very high sampling rates and multi-parameter fitting. Both these techniques need to reach ion saturation currents and therefore the power supply requirements are stricter than for the floating probe described here.

The main principle of the harmonics technique has been long known and its use in a tokamak plasma was more recently implemented in TEXTOR, albeit in a low bandwidth version. Subsequent measurements with higher temporal resolution (10 \( \mu \)s) were performed in the small tokamak TF-1 IVTAN (USSR), and the first evaluation of the technique for \( T_e \) measurements was performed in TEXTOR, where the low signal to noise ratio of the experimental setup limited its use to the scrape-off layer (SOL) plasma. Past work on this technique has used a technically incorrect expression for the probe current as is demonstrated in Sec. II.

This work reports results obtained with an advanced version of the experimental setup working at \( \approx 2 \mu \)s resolution and able to reach hotter and denser plasmas due to its implementation in a fast scanning probe. The technique described here is free from nonlocality problems since it uses a single probe tip and is subjected to lower power supply demands because the probe is floating. The high temporal resolution achieved makes this diagnostic an effective tool in investigations of fast plasma phenomena, transient plasma discharges, and as described in this article, tokamak edge turbulence.

Other improvements to the technique are reported, including the use of a Pearson transformer (high bandwidth, commercial version of a Rogowski coil) to measure the probe currents and matched multipole bandpass filters to improve bandwidth and reduce crosstalk between harmonics. We compare the data to \( T_e \) measurements obtained by means of a double probe located in the same probe head within 4 mm. A future application of this technique will be to provide measurements of turbulent heat conductivity at the tokamak edge which may be obtained by cross correlating the electric field and electron temperature fluctuations.

### II. BASIS OF THE TECHNIQUE

The technique is based on the nonlinearity of the single Langmuir probe characteristic. The current to the single tip, assuming Maxwellian populations, can be written as

\[
I_{pr} = I^+ - I^- \exp\left[2e(V_{pr} - V_s)/kT_e\right],
\]

where \( I^+ = 0.5en_Tc_s \) is the ion saturation current, \( I^- = 0.25en_Tc_e \) is the electron saturation current, \( c_s = [k(T_e + T_i)/m_i]^{1/2} \) is the thermal electron velocity, \( S \) is the effective collecting area, \( V_s \) is the plasma potential, \( V_{pr} \) is the probe potential, and \( m_i \) is the ion mass. In the experiments reported here, the probe is always floating dc wise due to the capacitor in series with the probe tip and we can write \( V_{pr} - V_0 = U_0 \sin \omega t \) when an oscillating potential of amplitude \( U_0 \) and frequency \( \omega \) is applied to a floating probe. The operating potential of the tip \( V_0 \) is different from the usual floating potential \( V_f \) as will be shown later. The periodic exponential term can be written in terms of Bessel functions \( I_k(z) \) of integer order \( k \)

\[
e^{-\cos \theta} = I_0(z) + 2 \sum_{k=1}^{\infty} I_k(z) \cos(k \theta).
\]

The probe current density can be written as

\[
I_{pr} = \frac{en_Tc_s}{4} \left[ e^{\frac{V_0 - V_f}{kT_e}} I_0 \left( \frac{U_0}{kT_e} \right) + \sum_{m=1}^{\infty} I_m \left( \frac{U_0}{kT_e} \right) \cos(m \omega t) \right].
\]

Note that the expansion of the exponential produces a dc (nonoscillating) current term that has to be accounted for when the floating condition \( I_{pr}^{DC} = 0 \) is implemented in order to solve for the operating potential \( V_0 \). The operating potential is that at which the total dc current (including the ac-generated current or rectification current) to the probe is zero. Thus

\[
I_{pr}^{DC} = \frac{en_Tc_s}{4} \left[ e^{\frac{V_0 - V_f}{kT_e}} I_0 \left( \frac{U_0}{kT_e} \right) \right] = 0.
\]

We can calculate the operating potential as

\[
eV_0 = eV_f + kT_e \ln \left[ \frac{4c_s}{c_e} \frac{1}{I_0} \left( \frac{U_0}{kT_e} \right) \right] = eV_f + kT_e \left[ \ln \left( \frac{4c_s}{c_e} \right) - \ln I_0 \left( \frac{U_0}{kT_e} \right) \right] = eV_f - kT_e \ln I_0 \left( \frac{U_0}{kT_e} \right).
\]

The usual logarithm of the ratio of speeds is now divided by the Bessel function of order zero. The last term on the right-hand side is written in terms of the standard floating potential \( V_f \) and it is clear that the net effect of the new term is to shift the operating voltage of the probe to a value below \( V_f \). This effect is a self-bias caused by an oscillating potential in the
plasma or probe and is well known in the plasma-processing community. The correction term is based on the Bessel function $I_0$, which equals one for zero amplitude of the applied voltage $U_0$, and increases rapidly with amplitude as shown in Fig. 1. For $eU_0/kT_e = 1$, $I_0$ equals 1.31, leading to a lower floating potential by $\sim kT_e \ln(1.31) = 0.3kT_e$.

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It should be noted that previous work in this subject $^{21–23}$ ignored the dc term due to the oscillating potential and was therefore carried out using an expression for the probe characteristic

$$I_{pr} = I^+ \left[ 1 - \frac{1}{I_0} \left( \frac{U_0}{kT_e} \right)^e \right]$$

where the first two terms (dc terms) cancel out at all times, as they should for a dc decoupled probe, and we are left with only the ac terms

$$I_{pr} = I^+ \left[ 1 - \frac{1}{I_0} \frac{U_0}{kT_e} \right] + 2 \sum_{m=1}^{\infty} I_m \left( \frac{U_0}{kT_e} \right) \cos(m \omega t)$$

$$= 2 \sum_{m=1}^{\infty} I_{m\omega} \cos(m \omega t); \quad I_{m\omega} = I^+ I_m (eU_0/kT_e) / I_0 (eU_0/kT_e)$$

(3)

It should be noted that previous work in this subject $^{21–23}$ ignored the dc term due to the oscillating potential and was therefore carried out using an expression for the probe characteristic

$$I_{pr} = I^+ [1 - e^{U_0 \cos(\omega t)/T_e}]$$

$$= I^+ \left[ 1 - \left( I_0 \frac{eU_0}{T_e} \right) + 2 \sum_{m=1}^{\infty} I_m \left( \frac{eU_0}{kT_e} \right) \cos(m \omega t) \right]$$

which is technically incorrect because the probes used in past work were dc floating (as the one used here) and no dc current should be present; but in practice, for small applied-voltage amplitudes, $eU_0/kT_e \ll 1$, the inaccuracy is small as long as $I_0 \approx 1$.

The Bessel functions, $I_m (eU_0/kT_e)$ have an argument depending solely on the amplitude of the applied voltage and the electron temperature. The creation of multiple harmonics $m\omega$ when the probe is excited by a frequency $\omega$ is then understood as caused by the nonlinearity of the probe characteristic. The evaluation of $T_e$ is possible from the ratio of any two harmonics of the probe current. However, since the harmonic amplitude $I_{m\omega} (eU_0/kT_e) / I_0 (eU_0/kT_e)$ falls rapidly with $m$, its detection from the background noise soon becomes impractical. The ratio of two harmonics $I_{m\omega}/I_{n\omega}$ is independent of the zero-order Bessel function correction, which cancels out, and therefore previous work on this subject $^{21–23}$ is essentially correct. Inspection of Figs. 2(a) and 2(b) makes evident that the ratio $I_{2\omega}/I_{\omega}$ features higher sensitivity than that of other low harmonics for a given $eU_0/kT_e$, and therefore such ratio is used here

$$\frac{I_{2\omega}}{I_{\omega}} = \frac{2I^+ I_2}{2I^+ I_1} = f(U_0/kT_e).$$

(4)

The ratio of the first two harmonics is fairly linear with $eU_0/kT_e$ up to $eU_0/kT_e = 1–2$, as shown in Fig. 2, and rolls over above that value, implying loss of sensitivity.

It must be noted that large values of $eU_0/kT_e$ cannot be treated properly by Eq. (1) because it does not include the electron saturation branch which occurs when $eU_0/kT_e \sim 3.5$, although in reality Eq. (1) is probably inaccurate before then. Furthermore, experimental work $^{26}$ has shown that the description embodied in Eq. (1) breaks down for $V_{pr}$

![Figure 1](image1.png) \hspace{1cm} ![Figure 2](image2.png)
\( \approx V_f \sim kT_e \) roughly corresponding to \( eU_0/kT_e \gg 1.0 \) and heretofore considered a practical (albeit somewhat arbitrary) limit for the harmonic technique.

To evaluate \( T_e \) in practice, the amplitudes of the first two current harmonics \( I_1 \) and \( I_2 \) are separated by analog filtering, their ratio calculated and the value of \( eU_0/kT_e \) corresponding to that ratio is obtained by inversion of Eq. (4). Calculation of the inversion is computer intensive and can be simplified by using tabulated values and interpolation or a linear expansion valid for \( eU_0/kT_e < 1 \) as seen next.

A. Approximation by series expansion

The Bessel functions can be expressed in a series expansion given by

\[
I_k(z) = \sum_{n=0}^{\infty} \frac{z^{2n+k}}{2^{2n+k}(n+k)!n!}.
\]  

An analytical expression for the amplitude of the first three harmonics can be obtained by taking the first term of the expansion with the condition \( eU_0/kT_e < 1 \)

\[
I_1(eU_0/kT_e) = \frac{eU_0}{2kT_e},
\]

\[
I_2(eU_0/kT_e) = \frac{1}{8} \left( \frac{eU_0}{kT_e} \right)^2
\]

\[
I_3(eU_0/kT_e) = \frac{1}{48} \left( \frac{eU_0}{kT_e} \right)^3.
\]  

The amplitude of successive harmonics decays very rapidly. For \( eU_0/kT_e \sim 0.5 \) we obtain that

\[
I_1 = 8I_{2w} \quad \text{and} \quad I_2 = 94I_{3w}.
\]

If we use the ratio of the first two harmonics, the temperature can be expressed as

\[
kT_e = \frac{eU_0 I_1}{4I_2}.
\]  

The exact (Bessel) \( I_2/I_1 \) ratio is compared to the series approximation in Fig. 3. Quite reasonable accuracy is achieved. When \( eU_0/kT_e = 1/2 \) the error is about 1%, as seen in Fig. 3(b), increasing 5% when \( eU_0 = kT_e \) and diverging rapidly thereafter.

For a given harmonic ratio, the exact expression gives a higher \( eU_0/kT_e \) ratio for a fixed \( U_0 \) and therefore a lower temperature than the series approximation. This effect will be most important for low temperature plasmas, i.e., far into the SOL where \( eU_0/kT_e > 1 \).

B. Influence of plasma density and potential fluctuations

Since the plasma potential and density in the tokamak boundary are fluctuating, some current will be driven in the external probe circuit (Fig. 4) which is floating with respect to the plasma in the dc sense. The main effect of potential fluctuations is a shift of the operating point along the probe characteristic. In general, this effect is not important as long as the operating point belongs to the exponential portion of the probe characteristic and is not approaching the electron branch. In order to evaluate the effect of potential fluctuations, we can write the probe potential as

\[
V_p = V_e + U_0 \sin \omega t - \langle \bar{V}_s \rangle - \bar{V}_s,
\]  

where \( \bar{V}_s \) reflects fluctuations in the plasma potential, the term \( \langle \bar{V}_s \rangle \) drives no current due to its definition and \( V_e \) is the potential drop across the isolating capacitor. We will use Eq. (1)

\[
I_p = I^+ - I^- \exp[e(V_e - \langle \bar{V}_s \rangle - \bar{V}_s + U_0 \sin(\omega t))/kT_e]
\]

\[= I^+ I^- \exp[e(V_e - \langle \bar{V}_s \rangle)/kT_e] \times \exp(-e\bar{V}_s/kT_e)
\]

\[
\times I_0 \left( \frac{eV_0}{kT_e} \right) + 2 \sum_{m=1}^{\infty} I_m \left( \frac{eV_0}{kT_e} \right) \cos(m\omega t).
\]  

This expression is only valid when the potential fluctuations interact linearly with each other and the exciting voltage. The plasma potential fluctuations are included into all the
current harmonics as $e^{\frac{eV_s}{kT_e}}$ and will cancel out when the ratio of two harmonics is computed. The frequency components of the fluctuations do not overlap due to the filters and the frequency and bandwidth choices. Parallel reasoning applies to the effects of density fluctuations on the $T_e$ measurement. The method is therefore intrinsically insensitive to plasma fluctuations.

It is to be noted that for typical TEXTOR plasma conditions, with $eV_s/kT_e < 0.6$, the applied oscillations remain in the exponential part of the probe characteristic. In the event of very high potential fluctuations, the operating point of the probe will shift towards the ion saturation region as discussed in Sec. II.

III. EXPERIMENTAL SETUP

The dc floating probe tip is incorporated in a fast scanning probe located in the outer midplane of the tokamak and excited by an external 300 W rf amplifier, driven by a function generator at 400 kHz. A block schematic of the system is presented in Fig. 4, and the components of the system will be described in detail in the upcoming sections. The power amplified rf signal from the function generator is applied between the probe pin and ground. The tip is made to float by including a capacitor in series. The current flows from the rf power supply, through the isolating capacitor to the probe tip, through the plasma and back to ground. The 0.068 μF isolation capacitor in series with the tip can withstand 3 kV.

A. Probe

The fast reciprocating probe system in TEXTOR, described in detail elsewhere, features a probe head with five graphite tips assembled on a boron nitride matrix. All but the foremost 0.5 cm of the head is covered by a graphite shroud 15 cm long and 2.5 cm in diameter. The probe is inserted into the plasma by a pneumatic mechanism for about 300 ms during the stationary portion of the TEXTOR discharge. The inward plunge lasts about 80 ms while outward plunge lasts 120 ms. The dwell time is 80 ms. Data are acquired continuously during the probe insertion and retraction and thus radial profiles are obtained. The probe system cabling, shaft construction, feedthrough, and external circuitry support a bandwidth of dc to 3 MHz. One of the probe tips (1.5 mm long and 1.5 mm in diameter) was used for the $T_e$ measurements using the technique reported here while two other tips were connected to a double probe system to provide a direct comparison of the results by both methods.

Driver stage

Since we will apply the technique to tokamak edge fluctuations, we need to evaluate the operating frequency and bandwidth we must detect. The typical frequency and bandwidth of edge plasma turbulence in tokamaks are well known. For TEXTOR the power of the microturbulence peaks at 50 kHz or less and decays quickly down a factor of

FIG. 4. Block diagram of the experimental setup. The alternative detection stages are shown surrounded by a box. The center-tapped transformer is shown attached to the circuitry, whereas the simple transformer is shown in a separate box.
100 at 150–250 kHz. In order to record the $T_e$ fluctuations, the driving frequency has to well be above the frequencies of plasma fluctuations, i.e., $f > 200$ kHz.

The voltage to temperature ratio must be maintained in the range $0.5 < \frac{eU_0}{kT_e} < 1.5$ (ideally $\frac{eU_0}{kT_e} = 1$) as discussed in Sec. III. The driving stage must have low output impedance, work at 400 kHz, and drive $\sim 1$ A current at 200 V (200 W). The typical amplitude driven by the amplifier used in these experiments was 40–60 V.

The condition $Z_{\text{out}} \ll Z_{\text{sheath}}$ must be met. In other words, a significant voltage divider between the probe sheath and driver stage output has to be avoided, otherwise the voltage applied to the probe tip would be a function of plasma parameters (local plasma density and electron temperature). This would result in significant perturbations of the $T_e$ measurements by plasma density fluctuations. In addition, the RC filter formed by the sheath impedance and the isolating capacitor must be considered about 200 kHz for these experiments. Due to concern about disruptions, TEXTOR requirements are that the output circuit of the amplifier is electrically isolated up to a voltage of 5 kV. We achieve this requirement by using inductive coupling by means of a transformer. The secondary of the transformer was configured in two different ways, to be discussed later, to reduce capacitive leakage current.

For the variety conditions in the tokamak boundary plasma ($10^{17}$ m$^{-3} < n < 10^{19}$ m$^{-3}$ and 10 eV $< T_e < 100$ eV), the probe sheath impedance varies typically in the range of 500 $\Omega$–1 k$\Omega$. Therefore we need $Z_{\text{out}} \ll 100$ $\Omega$. The current amplifier used features an output impedance of 50 $\Omega$ in parallel with a 50 $\Omega$ load and the primary of the transformer, providing optimal loading conditions for the rf amplifier and resulting in an output impedance of 25 $\Omega$.

**B. Detection stage**

Two different configurations of the secondary of the coupling transformer, i.e., the detection winding, were implemented. The two configurations are shown in Fig. 4. In the first configuration, one terminal of the winding is connected directly to ground and the other to the tip, where the current detection is performed. The second configuration cancels the leakage current produced by the stray capacitance of the coaxial cables inside and outside the vacuum ($\sim 700$ pf). In the second configuration, a secondary winding with a central tap is used. One terminal of the secondary is connected to a dummy cable that balances the capacitance of the probe cables, the other terminal is connected to the tip as before and the central tap, where the current detection is performed, is connected to ground.

The detection system should contribute as little as possible to the impedance of the probe current loop as discussed above. Traditionally the detection system used a shunt resistor and precautions had to be taken to isolate the output to protect electronics from tokamak disruptions. These two considerations make preferable the use an inductive current-detection unit; we have implemented a commercial current sensor, dubbed a Pearson transformer, as our detection coil. The sensor has a bandwidth of 0.1 Hz–3 MHz. The output of the Pearson transformer is fed to a low noise, high bandwidth amplifier followed by the two bandpass filters in parallel. The bandwidth of the filters needs to be chosen as to pass the whole spectral range $\Delta f$ of $T_e$ fluctuations ($\Delta f < 200$ kHz); i.e., within the range from $f_0 - \Delta f$ to $f_0 + \Delta f$. Passive multipole bandpass filters tuned to the frequencies of the first (400 kHz) and second (800 kHz) were commercially built by TTE, Inc. and are designed for a sharp cutoff as shown in Fig. 5. The filters have a $1/e$ width of $\sim 120$ kHz and are

![Fig. 6. A more circuit schematic, showing the detection stage, the filter stage, and the peak detector stage.](image)
matched within 2%, so that the ratio of transmissivities is nearly unity up to, and above, 200 kHz. The frequency range of the $T_e$ measurement can thus be somewhat extended.

C. Peak detector

The output of the filters, i.e., the first and second harmonics modulated up to $\sim 120-200$ kHz, is fed to high bandwidth amplifiers, as seen in Fig. 6, and subsequently to a peak detector system as shown in Figs. 4 and 6. The harmonics are half rectified and the amplitude of the resulting signal is detected using a peak detector that uses the sample and hold technique. The full circuit schematic is shown in Fig. 6. The sample and hold circuit samples the amplitude of the harmonics continuously until it receives a signal to hold the value from the peak detector. The value of the peak is then held as output until a new peak is detected. The circuitry thus samples peak values every 2.5 and 1.25 $\mu$s for the 400 and 800 kHz channels, respectively.

D. Novel features of the diagnostic

(1) Incorporation of the system on a fast scanning probe at TEXTOR.

(2) Electrically isolated, low output impedance driver stage.

(3) Nonresistive, high-bandwidth current detection.

(4) Use of advanced circuitry, including track and hold peak detection and ultralow noise, high bandwidth amplifiers.

(5) Use of both compensated and noncompensated coupling setup to reduce parasitic currents.

(6) Bandwidth $\sim 200$ kHz.

IV. MEASUREMENTS

The experiments were performed in TEXTOR ohmic discharges with central averaged-density $\bar{n}_e$ of 1–4
For these plasma boundary conditions 

\[ \frac{d}{\rho_e} \geq 1 \]

\[ \rho_e = 0.01 \text{ mm} \], where \( \rho_e \) is the electron Larmor radius. The probe measurements were performed at 1.1 s, during the flat-top phase of the discharge. The fast scanning probe was inserted into the plasma up to \( r = 43 \text{ cm} \).

The raw signals of the first and second harmonics, from the scrape-off layer (SOL) to the point of furthest penetration, are shown in Fig. 7. The first harmonic current is highest and increases as the probe penetrates the plasma and reaches a maximum for the time of deepest penetration. The ramp up of the signals represents the saturation current (plasma density and temperature) and the ratio \( eU_0/kT_e \) (essentially \( kT_e \) since \( eU_0 \) is constant) during the travel of the probe across the boundary plasma. The observable fluctuation level in the signals is produced by fluctuations of plasma density, plasma potential, and electron temperature at the probe location in the plasma. However, the ratio of these signals is dependent on electron temperature only as discussed previously.

The temperature was calculated from the exact, Bessel function based, harmonic ratio and also from the series approximation. The power spectrum of \( T_e \) is shown in Fig. 8 and it extends to \( \sim 200 \text{ kHz} \) as expected. The radial profile of time-averaged electron temperature (over 300 points), is displayed in Fig. 9 as derived from both the exact and series approximation calculation, where it decreases rapidly from \( T_e = 80 \text{ eV at } r = 42 \text{ cm} \) to \( 15-20 \text{ eV at the limiter radius} \). The temperature derived from the series approximation is slightly higher than the exact solution for high \( eU_0/kT_e \), as expected. The ratio of \( eU_0/kT_e \) is calculated and displayed in Fig. 9. When the ratio \( eU_0/kT_e \) is approximately 3 \((r = 46.4 \text{ cm})\) a sudden drop in \( T_e \) is seen, behavior which corresponds to the probe approaching or entering electron saturation and therefore departing from the nonlinear regime that allows the mathematical description deployed in Eq. (9). The \( T_e \) data from \( r = 45.5 \) to 50 cm are questionable or invalid since \( eU_0/kT_e > 1.5 \).

A discussion of why the valid data is limited only to a fraction of the probe plunge is in order. The amplitude of the oscillating voltage applied to the probe is kept constant. The ratio of applied voltage amplitude to electron temperature is thus lower in the core plasma \((eU_0/kT_e = 0.5 \text{ in Fig. 9})\) than in the SOL plasma \((eU_0/kT_e = 1.2-3 \text{ in Fig. 9})\). Ratios \( eU_0/kT_e \) higher than \( \sim 1.5 \) will result in excursions towards the electron saturation branch and therefore invalidate the model [Eq. (1)] used to derive the treatment discussed here. Varying the applied voltage to keep \( eU_0/kT_e \) within bounds can overcome this limitation as will be discussed later.

A comparison of the \( T_e \) profile obtained from the harmonics technique and that obtained by a double probe is made in Fig. 10. The agreement is very good up to \( r = 47 \text{ cm} \), where the series approximation breaks down since \( eU_0/kT_e > 1 \).

The normalized root-mean-square fluctuation level of \( T_e \), \( T_{\text{rms}}/T_e \), is presented in Fig. 11 for another discharge. As it follows from the plot \( T_{\text{rms}}/T_e \) varies from 0.3–0.5 in the edge plasma to \( >0.5 \) in the SOL \((r > 46.0 \text{ cm})\). The measured relative level of fluctuations is close to that observed in the boundary plasma of the TJ-1\textsuperscript{15} tokamak at \( T_{\text{rms}}/T_e = 0.4-0.5 \) and larger than that seen at TEXT\textsuperscript{27} at \( T_{\text{rms}}/T_e = 0.1 \).
TABLE I. Measurements of normalized turbulent levels in the edge and SOL are compared for various tokamak devices.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Tokamak</th>
<th>( \hat{n}/n ) SOL</th>
<th>( \phi/kT_e ) SOL</th>
<th>( \hat{T}_e/T_e ) SOL</th>
<th>( \hat{n}/n ) edge</th>
<th>( \phi/kT_e ) edge</th>
<th>( \hat{T}_e/T_e ) edge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boedo</td>
<td>TEXTOR</td>
<td>0.2 – 0.3</td>
<td>0.3 – 0.7</td>
<td>0.4 – 1.0</td>
<td>0.1 – 0.3</td>
<td>0.2 – 0.4</td>
<td>0.2 – 0.5</td>
</tr>
<tr>
<td>Hidalgo</td>
<td>TJ-I</td>
<td>0.3 – 0.5</td>
<td>0.4 – 0.5</td>
<td>0.4 – 0.5</td>
<td>0.3 – 0.5</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Lin</td>
<td>TEXT</td>
<td>0.4</td>
<td>0.2 – 0.5</td>
<td>0.2</td>
<td>0.3</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Tsui</td>
<td>TEXT</td>
<td>0.3</td>
<td>0.2 – 0.5</td>
<td>&lt; 0.2</td>
<td>0.2</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>

A comparison of normalized turbulence levels in the edge and SOL of various tokamak devices, including temperature fluctuations, is presented in Table I. The results obtained with this and other techniques are comparable.

The effect of the level of \( T_e \) fluctuations observed in TEXTOR on the evaluation of \( \hat{n}/n \) from \( I_{sat}/I_{sat} \) can be quantified from

\[
(I_{sat}/I_{sat}) = [(\hat{n}/n)^2 + 1/4(\hat{T}_e/T_e)^2 + (\hat{n}_T_e/nT_e)]^{1/2}
\]

Assuming perfect \( n \) \( T_e \) correlation and anticorrelation and using the values for TEXTOR in Table I we obtain that the error in the determination of \( \hat{n}/n \) from \( I_{sat}/I_{sat} \) is \(-20\%\) and \(+30\%\). This error is of the order of the statistical spread in the data.

V. DISCUSSION AND FURTHER DIRECTIONS

We have discussed the fundamentals of the harmonics technique, limits of applicability, details of a new detection scheme and its ancillary circuitry, and alternative computational schemes. The newest implementation of the technique, in a fast scanning probe with enhanced bandwidth, allows measurements of turbulence in the edge of tokamaks. We have presented and discussed data obtained with the system in the TEXTOR tokamak. The method presented in this article provides a combination of many of the advantages of the single and double probe methods while avoiding some of their drawbacks, namely:

1. Provides \( T_e \) with high time resolution.
2. Requires the use of only one floating probe tip, thus reducing hardware demands while providing high spatial locality. The system operates near the floating potential, with voltage requirements \( 0.5 < eU_0/kT_e < 1.5 \) and operating far from saturation, reducing the power load on the tip and power supply requirements.
3. The ratio of harmonics, and therefore the measurement, depends on \( T_e \) only. The influence of other parameters, such as potential or density fluctuations, is ruled out, unlike the double and single probe technique.
4. No multi-parameter fit to the probe characteristic is required, such as in the fast sweep method, reducing computational demands.

Extension of this work can be done in two areas:

1. When implementing this technique in a fast reciprocating probe in tokamaks, the dynamic range of \( T_e \) encountered in a probe plunge is large \( (T_e \sim 5 – 150 \text{ eV}) \). An apparent dilemma then arises between the need to optimize the signal to noise ratio (i.e., increase \( eU_0/kT_e \)) and the need to maintain \( eU_0/kT_e \approx 1.5 \) to prevent incursions into the electron saturation branch or the activation of extraneous harmonics. This need can be addressed by adding a feedback loop that maintains \( 0.5 < eU_0/kT_e < 1.5 \), thus preventing saturation of the probe or sensitivity loss.

2. Bandwidth increase is desirable. The separation between the active harmonics must be higher than twice the desired bandwidth to prevent cross talk between harmonics. In this work, the maximum bandwidth possible is 200 kHz. Increased bandwidth can therefore be achieved by increasing the driving frequency (i.e., the distance between consecutive harmonics) or by utilizing nonconsecutive harmonics for the measurement. Given the difficulties of using higher harmonics for the measurement (i.e., higher frequencies and rapidly decreasing amplitudes), it is more practical to increase the driving frequency. A byproduct of increased carrier frequency is the need for a higher effective sampling rate.

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