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Design and Initial Test of a Reflectometer System for the STOR-M Tokamak

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Abstract

A single-channel, homodyne reflectometer with O-mode polarization has been assembled, tested and installed on the Saskatchewan Torus-Modified (STOR-M) tokamak. The reflectometer consists of a voltage-controlled oscillator (VCO) microwave source and an in-phase/quadrature (*I*/*Q*) mixer. The reflectometer can be operated at a fixed-frequency as well as a frequency-sweeping mode (12.4-18 GHz). Preliminary experiments using the new reflectometer have been conducted at a fixed-frequency of 17 GHz to study density fluctuations and turbulence in STOR-M and compared with Langmuir probe measurements at the plasma edge. The spectral analysis of fluctuation signals obtained during an ohmic STOR-M discharge has shown that the power spectrum of the reflectometer signal is similar to that obtained from the Langmuir probe signal. It has been found that the density fluctuations typically peak at ~ 40 kHz and decay following a power law at higher frequencies (> 100 kHz). The amplitude and phase of reflectometer signal have also been calculated from the *I*/*Q* outputs and spectrally analyzed. It has been observed that the amplitude and phase spectra contain density fluctuation features similar to that of the Langmuir probe spectra. It has also been observed that amplitude fluctuations dominate the reflectometer signal, based on the close agreement between the amplitude and reflectometer spectra.

Keywords: Reflectometer, Tokamak, STOR-M, Plasma Fluctuations, Turbulence.

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تصميم واختبار أولي لنظام قياس الانعكاسات لمفاعل توكاماك ستور– إم

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الملخص

تم تجميع واختبار وتركيب جهاز انعكاس أحادي القناة يعمل بأسلوب التجانس الترددي وباستقطاب من نوع O–mode على مفاعل ستور– إم من نوع توكاماك. يتكوّن جهاز الانعكاس من مصدر ميكروويف يعتمد على مذبذب يتحكم به جهد كهربائي ومزجٍ من نوع الطور المتطابق/التربيعي (I/Q). يمكن تشغيل جهاز الانعكاس بتردد ثابت أو بنمط مسح التردد ضمن النطاق (12.4 – 18 غيغاهرتز) . أُجريت تجارب أولية باستخدام جهاز الانعكاس الجديد عند تردد ثابت يبلغ 17 غيغاهرتز لدراسة اضطرابات وكثافة البلازما وظواهر الاضطراب في مفاعل ستور– إم، وتمت مقارنة النتائج بقياسات مسبار لانغموير (Langmuir) عند حافة البلازما. أظهرت التحليلات الطيفية لإشارات الاضطراب التي تم الحصول عليها أثناء التفريغ الأومي في المفاعل أن الطيف الترددي لإشارة جهاز الانعكاس مشابه للطيف الناتج عن إشارة مسبار لانغموير. كما تبيّن أن اضطرابات الكثافة تبلغ ذروتها عادةً عند حوالي 40 كيلوهرتز، ثم تتناقص وفق قانون أُسّي عند الترددات الأعلى (> 100 كيلوهرتز) . تم أيضًا حساب كل من السعة والطور لإشارة جهاز الانعكاس من مخارج الـ I/Q وتحليلها طيفيًا. لوحظ أن أطياف السعة والطور تحتوي على خصائص تقلبات الكثافة المشابهة لتلك الموجودة في أطياف مسبار لانغمير. كما لوحظ أن تقلبات السعة هي السائدة في إشارة مقياس الانعكاس، استنادًا إلى التطابق الوثيق بين طيف السعة وطيف مقياس الانعكاس.

الكلمات المفتاحية: مقياس الانعكاس، توكاماك، ستور-إم، تذبذبات البلازما، الاضطراب.

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1. Introduction

Reflectometry has been widely used in many tokamak devices to monitor electron density fluctuations in plasmas [1] as well as to reconstruct electron density profile [2]. Density fluctuations play an important role in understanding the plasma turbulence and anomalous transport which degrade the plasma confinement and the operation of nuclear fusion devices [3]. The basic principle of reflectometry technique is based on launching a microwave beam into the plasma and reflecting it at a density cutoff layer at which the index of refraction is zero [4]. The reflected wave is then mixed with a reference signal to extract the phase and amplitude fluctuations which depend on the nature of the density fluctuations in the vicinity of the cutoff layer. The use of the reflectometry technique is preferred to the Langmuir probes because of its non-invasive nature and the ability to change or scan the location of measurement deeper into the plasma by varying the microwave frequency.

The measurements of density fluctuations in the Saskatchewan Torus-Modified (STOR-M) tokamak were previously carried out by arrays of Langmuir probes [5] and by a fixed-frequency, single antenna O-mode reflectometer [6]. That reflectometer system used a reflex klystron microwave source tuned at 17 GHz. Moreover, a hybrid magic tee was used to mix the reflected and reference signals to produce the sum and difference signals required for the total reflected power and phase shift calculations. An upgraded single-channel, homodyne reflectometer system with O-mode configuration has been recently assembled and tested in the STOR-M tokamak. A voltage-controlled oscillator (VCO) is used as a microwave source for the new reflectometer. The reflected signal from the plasma is combined with a local oscillator signal from VCO in an in-phase/quadrature (I/Q) mixer to generate the in-phase and quadrature signals which are used to examine the amplitude and phase information of the reflected signal. The reflectometer can be operated in either fixed-frequency mode or frequency-sweeping mode. However, the preliminary experimental tests of the reflectometer shown in this work are conducted at a fixed frequency of 17 GHz.

This paper is organized as follows. The layout and main components of reflectometer system are described in Section 2. Section 3 highlights the preliminary experimental results obtained by the reflectometer during the normal operation of STOR-M. A short summary and conclusions are given in Section 4.

2. Experimental Setup

The single antenna reflectometer system used on the STOR-M tokamak (R = 46 cm, a = 12 cm, $B_t \leq 1$ T, $n_e \sim 1 \times 10^{19}$ m^{-3}, $T_e \sim$ 200 eV) is shown in Figure 1. It is a homodyne reflectometer consisting of a microwave source, E-H tuners, isolators, directional couplers, a horn, and an I/Q mixer. The waveguide (WR-62) is used in the reflectometer system which is rated for microwave frequencies in the range between 12.4 GHz and 18 GHz (Ku-band). The reflectometer system is launched at the mid-plane from the low field side through a horizontal port with a diameter of 96 mm. A 9.52 mm thick quartz window is used between the horn and the plasma. A double layer of microwave absorber sheet with an iris cut to the same port diameter is placed in front of the quartz window to minimize unwanted reflections from the tokamak chamber.

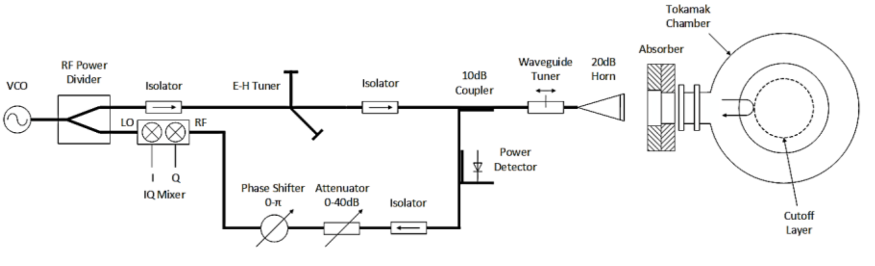

Figure 1: Layout of the homodyne reflectometer system in the STOR-M tokamak.

The microwave source is a 100 mW VCO source powered by an 8 V power supply. The VCO generates frequencies between 10 GHz and 20 GHz controlled by a voltage source with a maximum voltage rating of 17 V. A 15-18.2 GHz resonant-cavity frequency meter was used to characterize the frequency output of VCO. Figure 2 shows the oscillation frequency generated by VCO as a

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function of input control voltage. The control voltage of VCO was varied between 8.5 V and 14 V in 0.25 V increments to produce oscillation frequencies in the range of 15-18.2 GHz. The experimental data points can be fitted linearly as illustrated in Figure 2 by the dashed red line. The dashed vertical lines in the figure indicate the recommended frequency band of waveguide (WR-62) used in the reflectometer system which is in the range of 12.4 GHz and 18 GHz (Ku band).

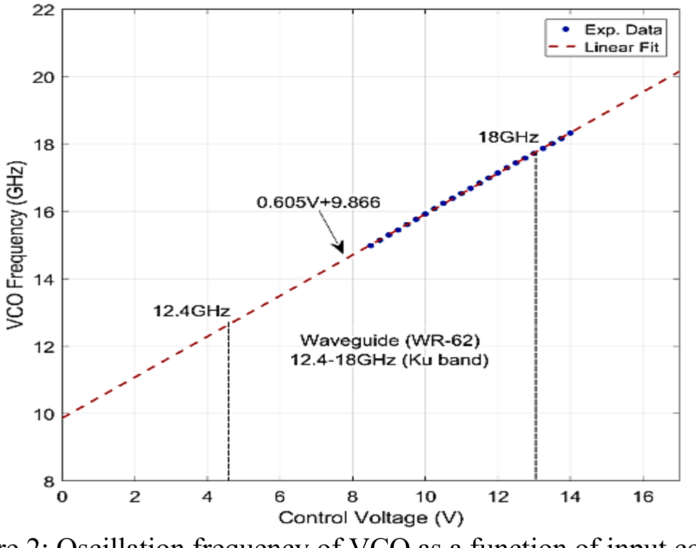

Figure 2: Oscillation frequency of VCO as a function of input control voltage. The vertical dashed lines indicate the frequency rating for the reflectometer waveguide (12.4-18 GHz).

The output beam from VCO is matched to the waveguide using an E-H tuner and is split into two waves using a power divider. One wave is used as a reference wave and the other as a probing wave. The probing wave is launched into the plasma using a 20 dB standard gain horn which acts as a transmitting and receiving antenna. The horn is oriented so that the electric field of the transmitted wave is parallel to the toroidal field and is reflected by the plasma at the O-mode cutoff layer. At the cutoff layer, the reflectometer frequency is equal to the local electron plasma frequency (f_{pe}). Part of the reflected wave from the plasma is then sampled by a 10 dB directional coupler which is matched to the horn using a slide-screw tuner, while the other part of the reflected wave is guided to the *I/Q* mixer.

The accessibility condition of the polarized O-mode waves is governed by the position of the cutoff layer inside the plasma, where the probing wave frequency equals the electron plasma frequency. However, in order to achieve an effective reflectometry, the probing wave must be reflected by the cutoff layer, or else will be absorbed at the resonance layer which is determined by the electron cyclotron frequency (f_{ce}). Figure 3 shows the characteristic plasma frequencies on the equatorial plane by assuming a parabolic density profile with line-averaged electron density ($\bar{n}_e$) of 5×10^{18} m^{-3} and toroidal magnetic field (B_t) of 0.55T as those are typical parameters in the STOR-M tokamak. As shown in Figure 3, the frequency of the polarized O-mode wave transmitted by the reflectometer should be higher than the electron cyclotron frequency at the plasma edge (12 cm), which is about 12.2 GHz.

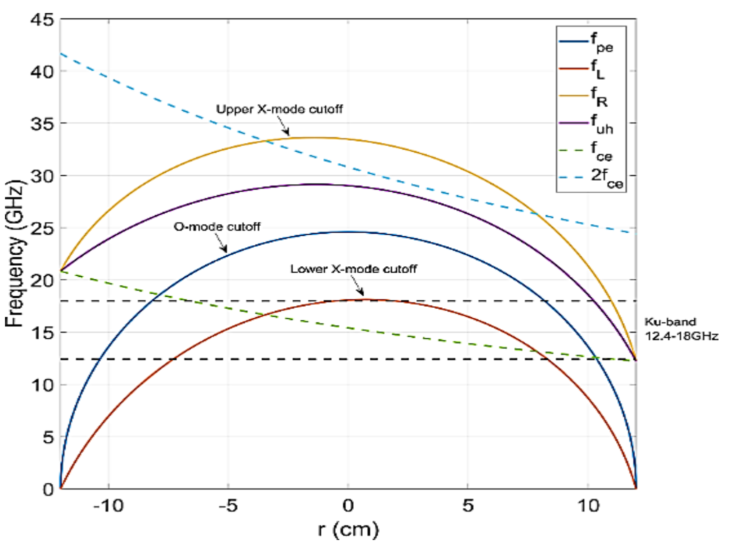

Figure 3: Characteristic plasma frequencies on the equatorial plane for typical STOR-M tokamak parameters ($\bar{\boldsymbol{n}}_e = 5 \times 10^{18}$ m^{-3}, $B_t = 0.55$T). f_{pe}: electron plasma frequency, f_L: left-hand cutoff frequency, f_R: right-hand cutoff frequency, f_{uh}: upper-hybrid frequency, f_{ce}: electron cyclotron frequency, $2f_{ce}$: 2nd harmonic of electron cyclotron frequency.

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Since the present reflectometer system in STOR-M operates in Ku-band regime (12.4-18 GHz), the plasma density profile can be radially scanned between 8.2 cm and 10.4 cm, depending on the line-averaged density and the toroidal field.

The reflected wave from the plasma and the reference signal from VCO are mixed in an I/Q mixer to produce the in-phase ($I(t) = A(t).\cos(\phi(t))$ and quadrature ($Q(t) = A(t).\sin(\phi(t))$ signals. The amplitude ($A(t)$) and phase ($\phi(t)$) of the reflected signal are then determined from I and Q output signals as follows [7]:

$$A(t) = \sqrt{I^2(t) + Q^2(t)} \tag{1}$$
$$\phi(t) = \tan^{-1}\left(\frac{Q(t)}{I(t)}\right) \tag{2}$$

Note that Equation 1 and Equation 2 contain both the time-averaged (mean) and time-varying (fluctuation) components of amplitude and phase, respectively. The fluctuating components of amplitude and phase carry statistical information on the density fluctuations and turbulence present in the plasma.

The reflectometer signal is collected by a calibrated power detector (1N78) attached to a 10 dB directional coupler on the reference path and amplified by a commercial Tektronix isolation amplifier (A6902B). The I/Q output signals pass through commercial narrowband amplifiers powered by a ±6 V DC power supply. The frequency response of the amplifiers was examined using an input signal with a fixed amplitude and variable frequency generated by a sinusoidal signal generator. Figure 4 shows the normalized output gain of the amplifiers plotted against the frequency of the input signal. The figure suggests that the amplifiers have an approximately flat frequency response between the lower cutoff frequency f_L = 3.5 kHz and the upper cutoff frequency f_H = 900 kHz, with the gain increasing below f_L and decreasing above f_H. The reflectometer and I/Q signals are digitized using National Instruments digitizer cards (NI PCI-6133) with a 14-bit resolution and a 2.5 MS/s maximum sampling rate per channel.

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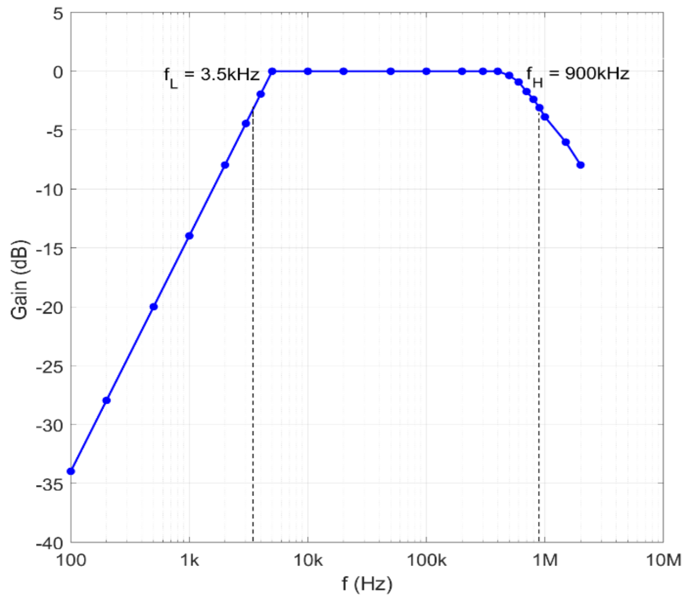

Figure 4: Frequency response curve of I/Q amplifiers. The amplifiers have a flat frequency response between 3.5 kHz and 900 kHz.

3. Experimental Results

Plasma density fluctuations and turbulence during an ohmic STOR-M discharge (shot no. 312289) have been investigated using the new reflectometer system and a Langmuir probe. A 4 mm microwave interferometer is used to measure the line-averaged electron density. The H_α emission intensity, integrated along the vertical chord across the plasma center, is monitored by a spectrometer. Figure 5 shows the following plasma parameters of the discharge (from top): (a) plasma current I_p, (b) loop voltage V_l, (c) line-averaged electron density $\bar{n}_e$, (d) horizontal plasma position ΔH, and (e) H_α emission intensity. The main plasma parameters for this ohmic discharge are $I_p = 20$ kA, $V_l = 2.5$ V, and $\bar{n}_e = 5 \times 10^{18}$ m^{-3} during the plasma current flattop phase.

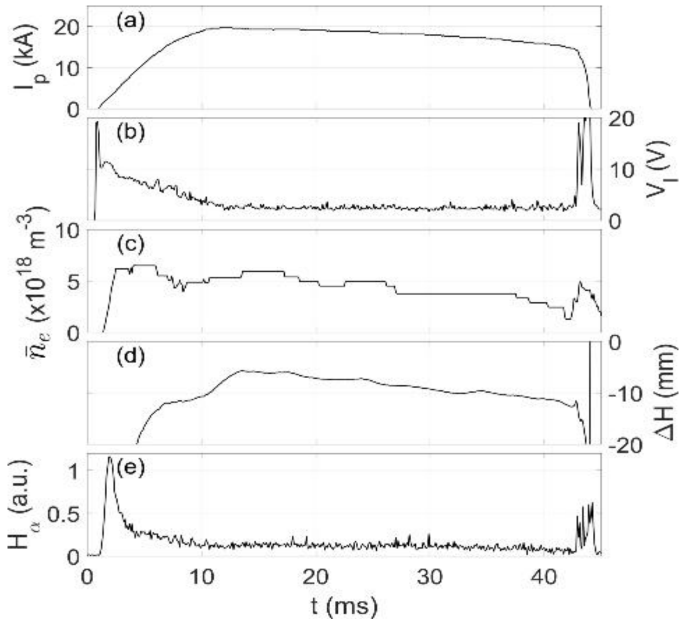

Figure 5: Typical ohmic STOR-M discharge (shot no. 312289): (a) plasma current (b) loop voltage (c) line-average electron density (d) horizontal plasma position (e) H_α line emission.

Figure 6 shows the waveforms of the following raw signals: (a) the reflectometer signal, (b) I signal, (c) Q signal, and (d) ion saturation current (I_{sat}). The frequency of the reflectometer system is fixed at 17 GHz (wavelength (λ) = 1.76 cm). The O-mode cutoff density for the reflectometer at 17 GHz is $n_c = 3.58 \times 10^{18}$ m^{-3}. The radial location of cutoff layer is estimated numerically [8] at $r \approx 8.7$ cm based on an assumed parabolic profile $n_e = n_0(1-(r/a)^2)$, corresponding to $r/a \approx 0.72$ in the plasma edge region. The ion saturation current is collected by a single-pin Langmuir probe biased at -95 V. The probe is inserted into plasma through a horizontal port located on the outboard mid-plane and toroidally separated from the reflectometer port by approximately 90°. The radial location of the Langmuir probe during this experiment is fixed at r = 10.6 cm (r/a = 0.88) which is the deepest location possible inside the plasma without disrupting the discharge.

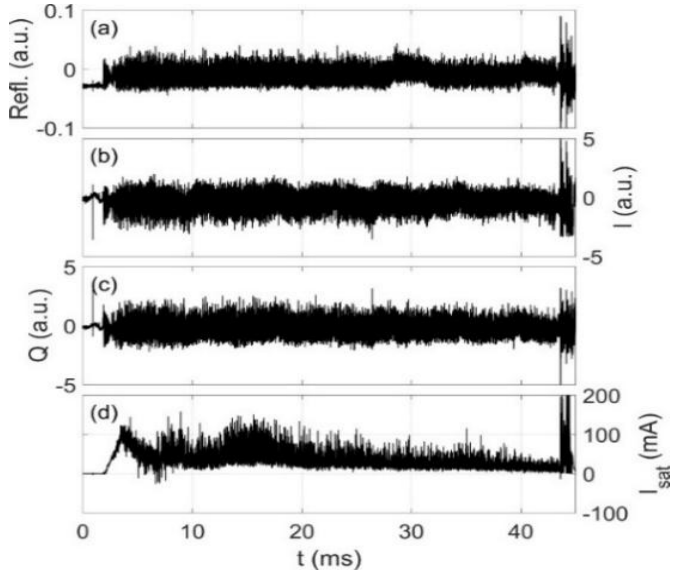

Figure 6: Time traces of (a) reflectometer signal, (b) *I* signal, (c) *Q* signal, and (d) ion saturation current for discharge no. 312289.

As mentioned previously in Section 2, the reflectometer can radially scan the plasma density profile over the range of 8.2-10.4 cm, depending on the line-averaged density and toroidal magnetic field. Therefore, since the Langmuir probe and reflectometer measurements are obtained at different radial and toroidal locations, the observed similarity between their signals should be interpreted as an indication of similar fluctuation characteristics rather than as evidence that both diagnostics measure exactly the same local plasma fluctuations.

During the plasma current start-up and decay phases, the reflectometer behaves like a double-pass interferometer when the plasma density at the center is below the cutoff value (3.58×10^{18} m^{-3}). During the plasma start-up phase, the reflectometer signal penetrates through the plasma and is reflected from the inner chamber wall on the high field side. Figure 7(a) illustrates the waveforms of *I* and *Q* signals during the plasma start-up phase. About 26 fringes can be seen for 0.8 ms before the density cutoff layer emerges in the plasma center at t = 2.6 ms, reverting the system back to the reflectometer regime. At the end of discharge, the reflectometer system functions once again as a double-pass

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interferometer when the core density drops below the cutoff value at around t = 46 ms. The fringe signals shown in Figure 7(b) last for about 1.6 ms, which is twice the duration of the start-up case but with a similar number of fringes (~ 26 fringes).

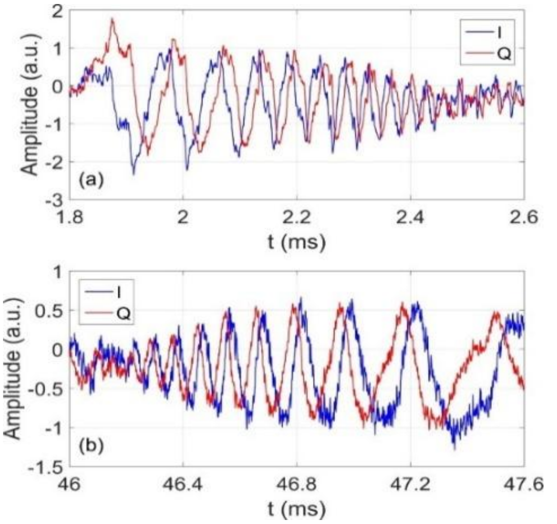

Figure 7: Fringe signals during (a) plasma start-up and (b) decay phases for discharge no. 312289.

The density fluctuations detected by the reflectometer and the Langmuir probe during the ohmic discharge no. 312289 were examined by spectral analysis. The time window (20-26 ms) was chosen for the analysis, which is located during the plasma flattop regime where the line-averaged density is mostly constant around $\bar{n}_e = 5 \times 10^{18}$ m^{-3} and the level of density fluctuations is high. The signals were sampled at a frequency of f_s = 1 MHz, corresponding to a sampling interval of 1 μs. A total of 6000 samples were acquired within the 6 ms analysis window, resulting in a frequency resolution of approximately 166.7 Hz. Figure 8(a) shows the expanded raw signals of the reflectometer and ion saturation current. Auto-power spectra of both signals are plotted in Figure 8(b) using a logarithmic scale to visually separate low frequency components (fluctuations) from high frequency ones (turbulence). Several frequency peaks below 150 kHz appear on both spectra. The spectra above 200 kHz are fitted by a power law (dashed lines in Figure 8(b)), which shows that the turbulent part of the reflectometer and Langmuir probe signals decays at a comparable rate of ~f^{-2}.

Figure 8(c) shows the cross-power and coherence spectra of the reflectometer and I_{sat} signals. A broad low frequency peak at ~ 5 kHz can be seen on the cross-power spectrum with a coherence coefficient below 10%. This frequency corresponds to the bursts seen on the raw signals in Figure 8(a) that occur periodically every 0.2 ms, similar to sawtooth crash period observed in STOR-M [9].

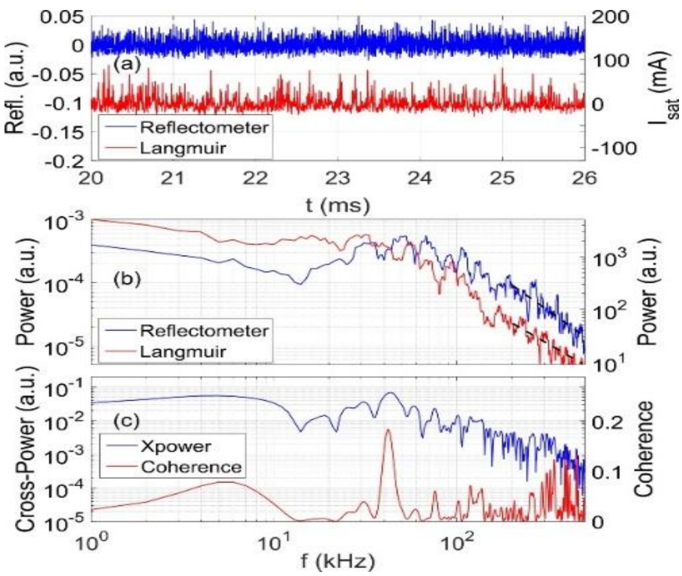

Figure 8: (a) Raw reflectometer and Langmuir probe signals during time window 20-26 ms, (b) corresponding auto-power, and (c) cross-power and coherence spectra.

Furthermore, the broadband activities between 20-40 kHz are magnetohydrodynamic (MHD) perturbations, which are often coupled with fluctuating signals measured by electrostatic probes in STOR-M. There are several mid-range density fluctuations between 50-150 kHz with coherence values around 10-20%, similar to density fluctuation features previously observed with the old reflectometer system in STOR-M [6]. The low coherence between the reflectometer and I_{sat} signals is a result of the toroidal separation of 90^0 between the reflectometer system and the

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Langmuir probe as well as the radial separation of the locations of the two different measurements.

The amplitude and phase of the reflectometer signal are calculated from I and Q signals using Equation 1 and Equation 2. As pointed out before, the amplitude and phase signals are comprised of mean and fluctuating components with the latter component carrying information on the plasma density fluctuations and edge turbulence. Figure 9(a) shows the auto-power spectra of amplitude and phase computed for the time window (20-26 ms). Both spectra carry similar frequency information observed on power spectra of the reflectometer and Langmuir probe signals. However, the power law fitting (dashed lines in Figure 9(a)) clearly shows that the turbulence regime (200-500 kHz) for amplitude and phase spectra falls off at different rates ($\sim f^{-2}$ and $f^{-0.2}$, respectively). The close agreement between the amplitude (Figure 9(a)) and reflectometer signal (Figure 8(b)) spectra indicate that the reflectometer signal is mostly dominated by the amplitude fluctuations in high-density ohmic plasmas [10]. signals.

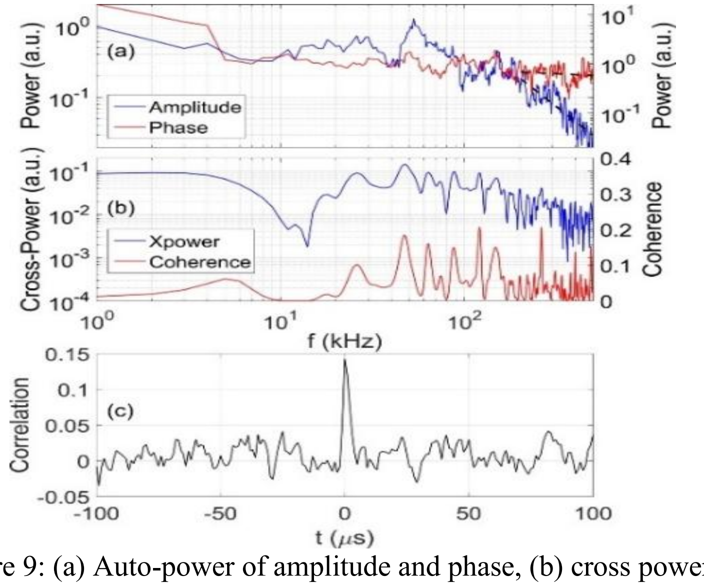

Figure 9: (a) Auto-power of amplitude and phase, (b) cross power and coherence spectra of reflectometer signals between the amplitude and phase, and (c) temporal cross-correlation between amplitude and phase signals.

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Figure 9(b) shows the cross-power and coherence spectra of amplitude and phase signals. Similar to Figure 8(c), low coherence (< 20%) density fluctuations between 50 kHz and 150 kHz in the presence of low frequency modulation (~ 5 kHz) and MHD frequencies (20-40 kHz) can be observed in Figure 9(b). The temporal cross-correlation shown in Figure 9(c) between the amplitude and phase fluctuations suggests a zero delay between the amplitude and phase

4. Conclusions

Edge density fluctuations and turbulence have been measured in the STOR-M tokamak by a newly installed reflectometer system. The system is a single-channel, homodyne reflectometer using a VCO module to generate microwave frequencies in the range of 12.4-18 GHz. The system launches a polarized O-mode wave from the low field side to the STOR-M plasma. The transmitted signal from the reflectometer is reflected from the cutoff layer and is then processed by an *I*/*Q* mixer to extract amplitude and phase information from the reflectometer signal. The fluctuations in amplitude and phase signals represent density perturbations and turbulence in the plasma. The reflectometer has a frequency-sweeping capability which has not been utilized at the present time. The preliminary experiments were carried out at a fixed frequency of 17 GHz.

The density fluctuations during an ohmic plasma discharge in STOR-M were measured by the reflectometer system and compared with density fluctuations collected by a Langmuir probe inserted at the plasma edge. The spectral analysis of the reflectometer and Langmuir probe signals has both revealed mid-frequency activities in the range of 50-150 kHz. The peak around 20-40 kHz corresponds to the MHD fluctuations and a low frequency component (~ 5 kHz) is likely related to sawtooth crashes. Furthermore, the density turbulence (200-500 kHz) in the reflectometer and Langmuir probe spectra decreased at a similar rate of $\sim f^{-2}$, as suggested by the power law fittings. However, the density turbulence in the amplitude and phase spectra dropped at rates of f^{-2} and $f^{-0.2}$, respectively. These results suggest that amplitude fluctuations are predominant in the reflectometer signals observed in STOR-M.

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References

[1] Mazzucato, E. *et al*. 1998. Microwave reflectometry for magnetically confined plasmas. *Rev. Sci. Instrum.* 69, 2201-2217.

[2] Simonet, F. 1985. Measurement of electron density profile by microwave reflectometry on tokamaks. *Rev. Sci. Instrum.* 56, 664-669.

[3] Wootton, A. J. *et al*. 1988. Fluctuations and anomalous transport (in tokamaks, particularly TEXT). *Plasma Phys. Control. Fusion* 30, 1479-1491.

[4] Laviron, C. *et al.* 1996. Reflectometry techniques for density profile measurements on fusion plasmas. *Plasma Phys. Control. Fusion* 38, 905-936.

[5] Dreval, M. *et al*. 2013. Plasma confinement modification and convective transport suppression in the scrape-off layer using additional gas puffing in the STOR-M tokamak. *Plasma Phys. Control. Fusion* 55, 035004.

[6] Conway, G. D. *et al*. 1996. Comparison of reflectometer fluctuation measurements from experiment and two-dimensional numerical simulation. *Rev. Sci. Instrum.* 67, 3861-3870.

[7] Hacquin, S. *et al*. 2006. Characterization of Alfvén cascades on the JET tokamak using a multi-channel O-mode reflectometer diagnostic. *Nucl. Fusion* 46, S714-S721.

[8] Hubbard, A. E. *et al*. 1987. A simple fixed-frequency reflectometer for plasma density profile measurements on JET. *J. Phys. E: Sci. Instrum.* 20, 423-427.

[9] Xiao, C. *et al*. 2008. Design and initial operation of multichord soft x-ray detection arrays on the STOR-M tokamak. *Rev. Sci. Instrum.* 79, 10E926.

[10] Rhodes, T.L. *et al*. 1998. Signal amplitude effects on reflectometer studies of density turbulence in tokamaks. *Plasma Phys. Control. Fusion* 40, 493-510.