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Upgrade of Reflectometry Profile and Fluctuation Measurements in Alcator C-Mod

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Abstract

This paper reports on the upgrade of the reflectometry profile and fluctuation measurements in Alcator C-Mod. The reflectometer consists of five amplitude modulated O-mode millimeter-wave channels operating between 50 GHz and 110 GHz. The system provides the electron density profile for densities up to 1.5×10^{20} m^{-3}. An upgrade has been implemented to improve the reliability of the system, eliminate 2π ambiguities in the group delay measurement, and enhance the fluctuation measurements. An upgrade of the 88 GHz channel has been installed, which allows fluctuations on both the upper and lower side-band signals to be measured independently with high resolution. Some preliminary fluctuation and density profile results are discussed.

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I. Introduction

The Alcator C-Mod tokamak is a high field (B_0 = 5-8 T), high density ($n_e > 1.0 \times 10^{20}$ m^{-3}), compact machine (R_0 = 0.67 m, a = 0.23 m). Proper H-mode pedestal studies [1] will require a high resolution edge density profile measurement. On Alcator C-Mod reflectometry currently provides our best edge density profile data, though without the spatial resolution to fully resolve the pedestal region. However, the reflectometer system described here does provide reliable information during L-mode operation, and a very useful upper bound on H-mode density scalelengths. The study of edge density fluctuations and turbulence in different H-mode plasmas has also become important, especially in Enhanced D_α H-mode [2], a type of H-mode first observed in Alcator C-Mod. A high resolution reflectometry fluctuation measurement will provide more information about plasma edge phenomena.

The reflectometer in the Alcator C-Mod tokamak is an amplitude modulated (AM) reflectometer working in O-mode [3]. It consists of five channels with center frequencies of 50, 60, 75, 88, and 110 GHz. The measured densities range from 0.31×10^{20} m^{-3} to 1.50×10^{20} m^{-3}.

AM reflectometry was originally proposed to improve the temporal resolution of the reflectometry system [4] [5] [6]. An AM reflectometer continuously measures the group delay to the critical surface on a time scale fast compared to changing plasma conditions. The modulation frequency should be chosen so small that less than one fringe needs to be tracked during the time of interest and the two critical layers are in the fluctuation correlation length (See the review article [7]). However, in the existing system, too high a frequency was initially chosen, and there were multiple fringe jumps in the phase measurement. Signal loss due to the frequency drift of the mm-wave sources was also a problem. Both issues have been solved in the upgrade.

The usual differential phase measuring scheme for AM reflectometry, i.e., measuring the phase difference between the upper (USB) and lower (LSB) side-bands of the AM waves, reduces fluctuation sensitivity compared to the base-band technique. The differential phase scheme effectively subtracts correlated fluctuations found in the USB and LSB signals. In order to study density fluctuations at the critical surface, the USB and LSB signals should be separated and measured independently. A prototype of such a system at 88 GHz has been developed and installed.

In Section II, the upgrade of the reflectometer is presented. The upgrade includes stabilizing the frequency drift of the mm-wave sources, reducing the AM modulation frequency, and installing a fluctuation measurement channel. Some preliminary results are presented in Section III. More issues about the reflectometer are discussed in Section IV.

II. Reflectometer Upgrades

A. Frequency Stabilization of Gunn Oscillators

The group delay detecting system includes narrow band-width filters and limiting amplifiers. This measuring scheme restricts the allowable frequency drift of the mm-wave sources (Gunn oscillators) to be less than ±5 MHz. The frequency of a Gunn oscillator depends on the bias voltage, varactor voltage, and temperature. Since all applied voltages are well controlled, frequency drift is mainly due to a change in ambient temperature. The drift can be as high as 10 MHz/^{0}C for Gunn oscillators in the frequency range of 50-110 GHz, which makes the system unreliable even under small variations in room temperature. A method that controls the temperature and stabilizes the Gunn oscillators frequencies has been implemented (Similar schemes used in reflectometry for fusion plasma have been reported, for example, [8]).

Fig. 1 shows the method used. A thermo-electric chip (TEC) is mounted onto an aluminum block, which is in thermal contact with the Gunn oscillator. The signal of the temperature sensor in the aluminum block is used to control the TEC, which can heat as well as cool the Gunn oscillator. The feed-back temperature control system controls the temperature of the Gunn oscillator to within ±0.1 ^{0}C, and stabilizes the frequency to within ±2 MHz during a run day. This control range is sufficient to keep all IF signals within allowable passbands.

B. Profile Measurement Upgrade

For O-mode reflectometry, the density profile is obtained by an Abel inversion of group delays [9]:

$$R_c(f_0) = R_{out} - \frac{c}{2\pi^2}\int_0^{f_0} \tau(f)\frac{df}{(f_0^2 - f^2)^{\frac{1}{2}}} \qquad (1)$$

where $R_c(f_0)$ is the critical surface position for the wave with frequency f_0, and R_{out} is the outmost plasma edge ($n_e(R_{out}) = 0$). As shown in Eq. (1), in order to obtain $R_c(f_0)$, one needs to measure the group delays, $\tau(f)$, of all frequencies $f < f_0$.

The AM profile measurement system, as shown in Fig. 2, measures the phase difference ($\Delta\Phi = \Phi_u - \Phi_l$) of the upper side-band (USB), $f + \Delta f$, and lower side-band (LSB), $f - \Delta f$, and determines the group delay $\tau = \frac{1}{2}\frac{\Delta\Phi}{\Delta f}$.

The modulation frequency, Δf, must be chosen carefully [7]. It cannot be too large or multiple fringes will have to be followed; but it cannot be so small as to seriously limit spatial resolution. The modulation frequency was initially set at 500 MHz for high spatial resolution. However, because of the short beat-wave wavelength, the measured $\Delta\Phi$ had several fringe jumps and tracking the phase could be difficult without manual intervention in the analysis process. A lower modulation frequency of 132.5 MHz is now used and has solves this problem. The use of I/Q (sin/cos) detectors provided more than adequate resolution ($\pm 3^0$) for density profile measurements. Limiting amplifiers in the phase detecting system also reduce the amplitude effects in the phase measurement.

The absolute group delay calibration obtained by assuming a mirror reflection from the vacuum vessel inner wall was found to be inadequate, possibly due to changes in coupling of the reflected waves into the horns, spurious reflections and over-moded waveguides. Instead, a combined profile derived from the two-color interferometer (TCI), Thomson scattering, and the fast scanning Langmuir probe are used to calibrate the reflectometer. The density profile below the lowest density measured by the reflectometer, 0.31×10^{20} m^{-3}, which is usually outside of the last closed flux surface (LCFS), can only be provided by the Langmuir probe. By assuming the reflectometer profile to be the same as the interpolated profile of the TCI, Thomson scattering, and the probe during the L-mode portion of the discharge, some offset corrections can be determined for group delays (Fig. 3).

C. Fluctuation Measurement Upgrade

A prototype system at 88 GHz (cutoff density $n_c = 0.96 \times 10^{20}$ m^{-3}) designed to study fluctuation specifically has now been installed. As shown in Fig. 4, the USB and LSB signals are separated by introducing a reference signal that is the mixed output of the two Gunn oscillators. The phases of the USB and LSB signals are measured independently. No limiting amplifier is used, thus both amplitude and phase fluctuations of the reflected signals can be studied. The new system measures the phase change of the base-band signal as do many other reflectometers, for which some models have been developed to explain fluctuations. This system also allows correlations between the USB and LSB to be studied.

III. Results

A typical profile evolution during the L-mode to H-mode (L-H) transition is shown in Fig. 5. The edge density profile steepens in less than 5 ms. The profile is obtained using the calibration method described in Section II (B). While the spatial error is still large due to calibration inaccuracy, the temporal resolution is adequate. The reflectometer easily follows fast changes of the density profile.

Some preliminary results from the upgraded fluctuation channel are also presented. Coherent frequencies are observed in H-mode phase, especially in Enhanced D_α (EDA) H-mode. Fig. 6 shows a case when the plasma undergoes H-mode to L-mode and back to H-mode transitions. Clear coherent frequencies are observed in the complex FFT power spectra, $|S(f)|^2$, during the H-mode phase. No coherent mode has been observed in L-mode. In Fig. 7, coherent frequencies clearly evident in EDA H-mode broaden and vanish when the plasma enters an ELM free period. Coherent modes are usually in the frequencies range of 100-150 kHz. As shown in Fig. 7, they are also modulated by sawtooth oscillations in EDA H-mode. The value of the center frequency is closely correlated to D_α signal level. The spectra are obtained by FFT analysis on the complex signal as has been discussed previously [10] [11]:

$$S(f) = \int E(t)\left[\cos\Phi(t) + i\sin\Phi(t)\right]e^{-i2\pi ft}dt \tag{2}$$

where $E(t)\cos\Phi(t)$ and $E(t)\sin\Phi(t)$ are the *sin* and *cos* outputs of the I/Q detector respectively.

IV. Discussion

As pointed out in [7] [12], etc., AM reflectomery can have difficulties separating the primary return from multiple reflections from the vacuum wall or other targets due to its limited range resolution. We believe these effects only affect the initial wall calibration since in the C-Mod design the plasma return signal should strongly dominate. Statements to the effect that multiple reflections are not detectable in AM systems assume static conditions. Any motion of the spurious targets or the plasma make them painfully obvious. Scans of the plasma position together with comparisons to probe, interferometer, and Thomson scattering data must be used to sort out these issues. Some compensating methods, such as adding mm-wave absorpent material on the nearby vacuum wall and sweeping the modulation frequency, which can average out most spurious signals, are also being considered. Improvements to the waveguide structure is also being considered in order to reduce sensitivity to both mechanical vibrations and coupling effects at the horns.

1-D models, 2-D models, models with scattering effects, and models considering specific critical surface structures have been developed to explain fluctuations measured by reflectometry (Ref. discussions in [11]). However, due to the complicated features of the problem, the physical meaning of fluctuations is still an open issue. How to express reflectometry fluctuations in terms of fundamental plasma parameters, such as the density fluctuation level and k-spectra, and how to relate the reflectometry fluctuations with other fluctuation diagnostics in Alcator C-Mod are still under study.

V. Summary

An upgrade on the reflectometer in Alcator C-Mod has been implemented. The upgrade has improved the reliability of the system, new high sensitivity fluctuation electronics has been added, frequency drift in the mm-wave sources has been stabilized, and 2π phase ambiguities in the group delay measurement have been eliminated. With improved calibration techniques, the Alcator C-Mod reflectometer should provide reliable density profile information during the next run campaign.

Acknowledgements

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Figure Captions:

Figure 1. **Gunn Oscillator Frequency Stabilization.** Depending on the level of temperature sensor signal, the thermo-electric chip (TEC) heats or cools the aluminum block, which is in thermal-contact with the Gunn oscillator. The temperature is controlled, thus the frequency is stabilized.

Figure 2. **Layout of Profile Measurement System.** The group delay is obtained by measuring the phase difference between the upper and lower side-bands. Limiting amplifiers reduce the amplitude effects in the phase measurement. The three waves, 132.5 MHz, 235 MHz, and 30 MHz, are derived from a single wave source.

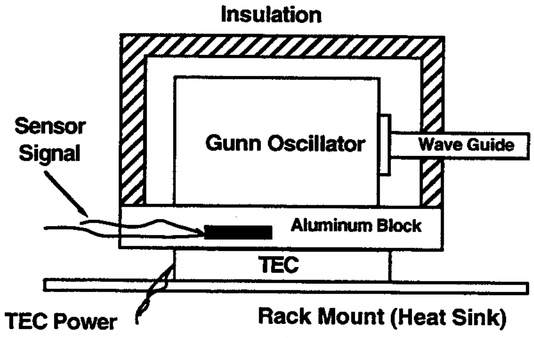
Figure 3. **Density Calibration.** At a time point (in L-mode) when probe data are available, a combined profile derived from the interferometer (TCI), Thomson scattering, and the probe provides the calibration for reflectometer data. Corrections to the group delays are determined by assuming that the reflectometer produces the same profile as the combined profile.

Figure 4. **Layout of the Fluctuation Measurement Channel.** A reference signal, 515 MHz, derived by mixing signals from the two Gunn oscillators is used to separate the upper and lower side-bands. The phases of the side-bands are measured independently (Only the USB is shown in the figure). The waves of 132.5 MHz and 500 MHz are derived from a single wave source.

Figure 5. **Profile Evolution during L-H Transition.** The edge profile measured by the reflectometer steepens rapidly in the L-H transition. The relative changes of positions have errors of less than 0.5 cm while the absolute positions have errors of less than 1 cm.

Figure 6. **Fluctuation Power Spectra $|S(f)|^2$ in L-H-L Transitions.** Coherent frequencies in the 100-150 kHz range are observed during H-mode phases, but no such coherent frequency occurs during L-mode operation.

Figure 7. **Fluctuation Power Spectra $|S(f)|^2$ in Different H-modes.** Coherent frequencies clearly evident in Enhanced D_α (EDA) H-mode broaden and vanish when the plasma enters an ELM free period. In EDA H-mode, The center frequency is modulated by sawtooth oscillations and correlates with D_α signal level.



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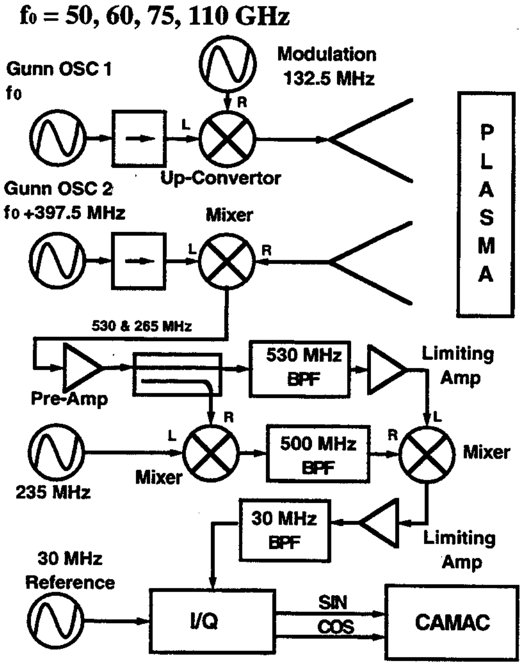

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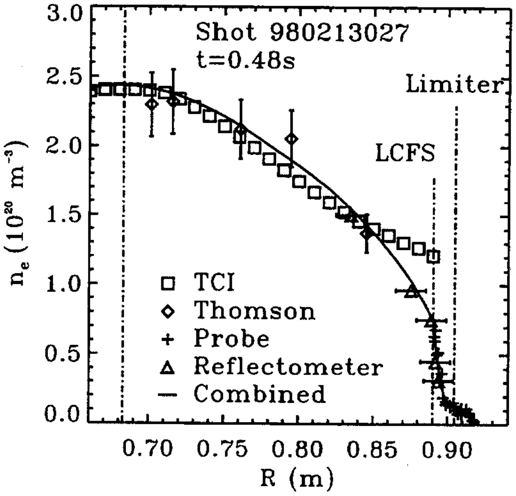
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LCFS
TCI
Thomson
Probe
Reflectometer
Combined
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R (m)
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1.5
1.0
0.5
0.0
0.70
0.75
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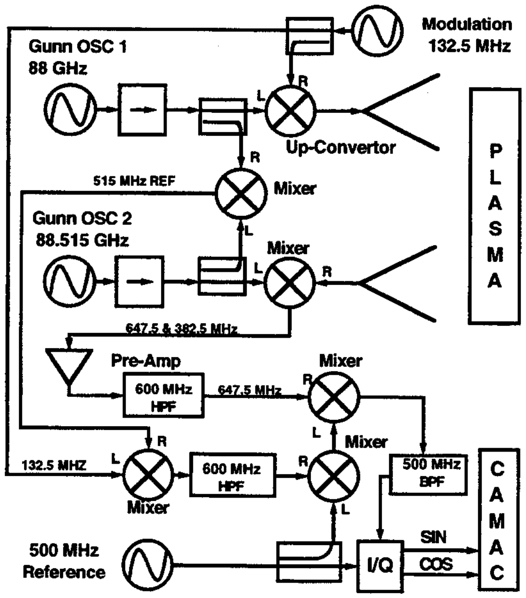
0.85
0.90

Figure 3: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Gunn OSC 1
88 GHz
L
R
Up-Convertor
R
515 MHz REF
Mixer
Gunn OSC 2
88.515 GHz
L
Mixer
L
R
P
L
A
S
M
A
647.5 & 382.5 MHz
Pre-Amp
600 MHz
HPF
647.5 MHz
Mixer
R
L
Mixer
R
132.5 MHZ
L
R
Mixer
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SIN
COS
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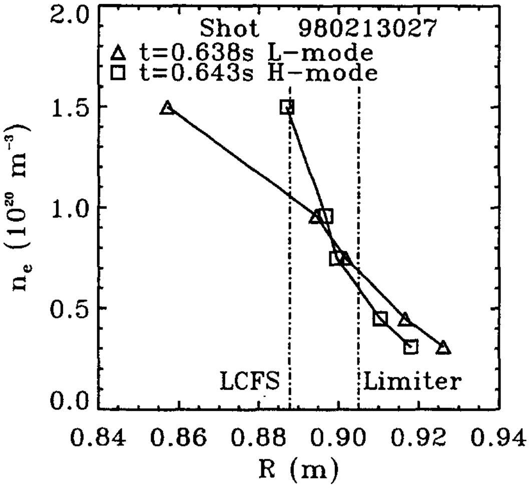
A
C

Figure 4:



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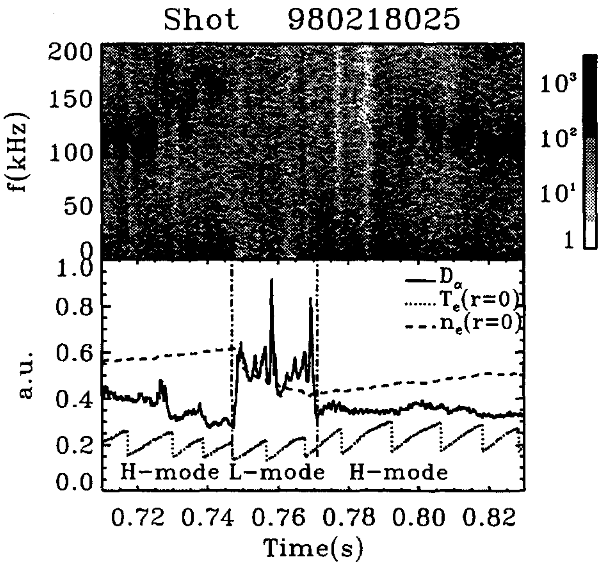
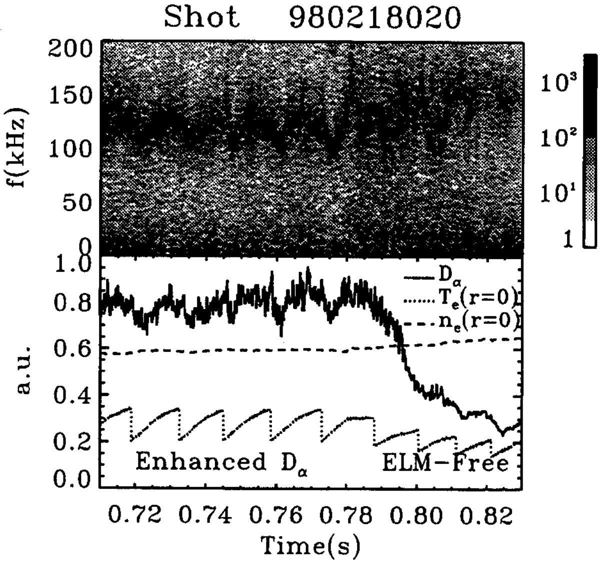


Figure 6: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D_α
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Enhanced D_α
ELM-Free
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0.80
0.82
Time(s)

Figure 7: