

# Application of fast reflectometer density profile measurements to investigate plasma instabilities in DIII-D

L. Zeng,<sup>a)</sup> E. J. Doyle, T. L. Rhodes, G. Wang, and W. A. Peebles

*Department of Electrical Engineering and PSTI, University of California, Los Angeles, California 90095*

K. H. Burrell

*General Atomics, San Diego, California*

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The high spatial ( $\geq 2$  mm depending upon plasma conditions) and temporal ( $10 \mu\text{s}$ ) resolution possible with the DIII-D solid state profile reflectometer system makes it possible to investigate profile modifications associated with plasma instabilities. In order to take full advantage of this fast sweep and high resolution capability, multiple issues had to be addressed, including fast data acquisition, large data acquisition memory depth, improved signal to noise, accurate profile start location, and finally fast accurate automatic data analysis. Improvements in all these areas make the profile reflectometer ready for plasma instability studies. In a demonstration of this capability, fast, high spatial resolution reflectometer measurements have been successfully used to investigate the edge harmonic oscillation (EHO) in the quiescent double barrier regime, as well as the edge localized modes (ELMs) on DIII-D. It is found that the scrape-off layer density profile is modulated at the EHO fundamental frequency. The edge density profile evolution is also tracked during ELMs, showing that the density profile expands to the vessel wall at the onset of Type 1 ELMs. © 2003 American Institute of Physics. [DOI: 10.1063/1.1527250]

## I. INTRODUCTION

For many years, reflectometry has been used for localized electron density profile measurements in plasmas. As a short-range radar measurement, profile reflectometry measures the phase or time delay of electromagnetic radiation reflected from a plasma cutoff layer.<sup>1</sup> By measuring the phase delay for a range of probing frequencies which are reflected at different plasma radii, the plasma electron density profile as a function of radius can be recovered using an inversion procedure.

Accurate profile reflectometer measurements have already made contributions to a range of physics studies on DIII-D.<sup>2,3</sup> However, previous DIII-D results focused on “average” profiles, which were usually derived by averaging reflectometer profiles from several full-band frequency sweeps. In this article we report on demonstrations of the ability of the DIII-D system to track fast profile modifications associated with magnetohydrodynamic (MHD) activity and edge localized modes (ELMs). In order to take full advantage of the fast sweep and high spatial resolution capability of the DIII-D system, multiple issues had to be addressed. These include fast data acquisition, large data acquisition memory depth, improved signal to noise, accurate profile start location, and finally a fast accurate automatic data analysis routine. In the following sections, these several issues are described, and demonstrations of the instability measurements with high time and spatial resolution are shown.

<sup>a)</sup>Electronic mail: zeng@fusion.gat.com

## II. IMPLEMENTATION OF FMCW PROFILE REFLECTOMETER WITH HIGH SPATIAL AND TEMPORAL RESOLUTION FOR PLASMA INSTABILITY MEASUREMENTS

Since the early 1990s the UCLA Plasma Diagnostic Group has pursued accurate reflectometer density profile measurements over the full range of plasma conditions encountered in the DIII-D tokamak.<sup>4–9</sup> Currently, there are two frequency modulation of a continuous wave frequency modulated continuous wave (FMCW) profile reflectometry systems working on the DIII-D tokamak. The first is a V-band (48–75 GHz) system using a backward wave oscillator source, while the other, which is utilized in this article, is a solid-state Q-band (33–51 GHz) system. The polarization of each system can be independently aligned so as to use either X-mode propagation (for edge profile measurement), or O-mode propagation (for core profile measurement). This flexibility allows a greatly increased spatial coverage of the plasma radius. Due to its solid-state source the Q-band system is ideal for fast sweep, high time resolution studies and that is the system that is focused upon here. The Q-band system uses an 8–12.5 GHz hyperabrupt varactor tuned oscillator microwave source followed by an active frequency quadrupler to get full band operation (32–50 GHz). With this source full-band sweeps in as little as  $10 \mu\text{s}$  are possible.

In order to make the best use of the very fast sweep system, a high performance PC-based data acquisition system was selected.<sup>9</sup> This system is based upon a 12 bit, 50 MHz sampling rate, dual channel PCI digitizer card with 1 MB on-board memory built by the GaGe company. The “real time” data transfer mode uses the PCI data bus (maximum data transfer rate of 100 MB/s) to transfer data directly

into PC memory, and has a memory depth of 30 MB per channel. Depending on the physics need, two typical operating modes with the PC digitizer are: (1) Burst mode (non-continuous) profile measurements during the duration of the plasma discharge, i.e., profiles are obtained at regular intervals throughout the discharge; or (2) continuous profile measurements for a more limited duration, such as 1.5 s. Using burst mode, the maximum sampling rate 50 MHz can be used, while data can be continuously taken for 1.5 s duration at 10 MHz sampling rate by using the continuous mode. This data acquisition system provides both the necessary high frequency sampling rate as well as the memory depth needed for physics studies on DIII-D.

Previous profile measurements on DIII-D typically averaged over multiple sweeps so as to improve the signal-to-noise ratio, a process which results in reduced time resolution. Because of variable magnetic field pitch angles, undesired reflections are produced if the directions of the microwave launching and receiving horns do not approximately match the *X*-mode (or *O*-mode) propagation directions. The spurious amplitude signal depends upon both the sine of the angle mismatch and the distance to the unwanted cutoff layer. Small angle mismatches ( $<5^\circ$ ) typically result in less than a 10% spurious signal level. A large angular mismatch can occur whenever either the plasma current or toroidal magnetic field directions are reversed and the polarization angle of the antennas is not changed to account for this. Under these conditions it was found that the signal-to-noise ratio was four times smaller than when polarization was optimized.<sup>10</sup> Thus, it is crucial to optimize the directions of launching and receiving horns for the probing wave propagation, in order to realize accurate profile analysis, especially for the high temporal resolution measurement when every profile is analyzed from only one individual frequency sweep data.

In order to simultaneously obtain both high range resolution and high precision profiles, smoothing and range resolution bandwidths need to be optimized in the analysis program.<sup>5,7</sup> The range resolution filtering is applied so as to remove spurious signals originating at locations other than the desired plasma cutoff layer. The smoothing bandwidth is applied to average the extracted phase shifts/time delays so as to increase the profile precision. However, too much smoothing will smear the profile, so an optimization of this parameter is also necessary. For *X*-mode edge profile analysis, magnetic field information is used in the profile inversion process. Hence, accurate EFIT data, which include plasma flux to spatial coordinate mapping information, are also important during reflectometer data analysis.

Analysis of thousands of profile data per discharge in DIII-D requires an accurate and fast automatic profile analysis program. Of major importance for automatic density profile data analysis is a routine to automatically detect the zero density start position. This is because the zero density start position can be determined from the *X*-mode propagation reflectometer data when the probing wave first encounters the right-hand cutoff layer in the plasma. The accurate determination of the radial position of the zero density start is important since the subsequent profile is reconstructed from

that location. An inaccurate start location can lead to a radially shifted profile. An improved robust method has been developed for the automated identification of the zero density start position in edge density profile measurements.<sup>10</sup> Using the technique, the standard deviation value of the automatically calculated frequency at the start point of reflection has been reduced to 0.04 GHz, corresponding to 2 mm standard deviation in the plasma radius. This development greatly reduces the uncertainties associated with automatic analysis and allows for efficient analysis of hundreds or even thousands of profiles in a reasonable amount of time. It should be noted that the positional accuracy of the measured plasma electron density profiles is not constant, but varies depending on local plasma conditions. From the analysis of reflectometer signal reflected from a flat mirror, the standard deviation of the measured distance is about 2 mm.<sup>10</sup>

Overall, the performance of the *Q*-band reflectometer system has been improved in several ways: In hardware, high performance digitizers are employed, and the microwave propagation polarization has been optimized. With regard to software analysis, an improved criterion for automated identification of the zero density start position has been implemented and adaptive optimization for data smoothing and range resolution has been improved. With the improvements, high spatial resolution reflectometer profiles are obtained from individual full-band sweeps, so that high time resolution (10  $\mu$ s) is achieved. The measurement has the capacity to investigate MHD instabilities in DIII-D. In the following sections two examples are presented which demonstrate the improved system capability.

### III. SOL DENSITY PROFILE MODULATION BY EHO

Profile reflectometer measurement with high temporal and spatial resolution can resolve the edge harmonic oscillation (EHO) which is a continuous magnetic and electrostatic oscillation, believed to provide the edge particle transport necessary for the quiescent double barrier (QDB) regime.<sup>11–13</sup> QDB plasmas are a sustained high performance steady state operating regime, combining internal transport barriers with a quiescent ELM-free *H*-mode edge (*QH* mode), giving rise to separate core and edge transport barriers. To date the nature of the EHO remains unclear.<sup>13</sup>

In order to get high resolution, accurate profile measurements during the EHO, several factors need to be considered carefully. As mentioned in the previous section, it is crucial for edge profile reflectometer measurements to optimize the directions of the launching and receiving horns in order to keep the probing wave in *X*-mode propagation. For QDB plasmas, the direction of the plasma current is reversed so as to obtain counter neutral beam injection. To compensate for this we realigned the directions of launching and receiving horns by adding a small angle-twisted wave guide in the reflectometer system to optimize its *X*-mode polarization for this experiment. Due to the “high” frequency range of the EHO (several kHz), the full frequency-band sweep time of the reflectometer was set to 10  $\mu$ s—much smaller than the EHO harmonic periods, in order to have as high as possible temporal resolution. The highest sampling rate, 50 MHz, of

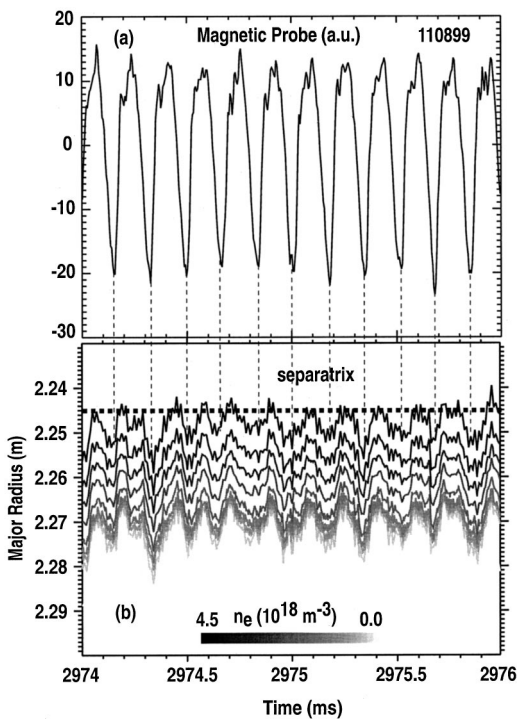


FIG. 1. For shot 110 899, (a) time history of the EHO signal detected by a midplane magnetic probe and (b) a contour plot of the spatial location of SOL density layers as a function of time, as measured by the  $Q$ -band reflectometer system. By a comparison of (a) and (b) it is apparent that the EHO is modulating the position of the SOL density layers.

the PC-based digitizer was used. The density profile perturbation, measured by the  $Q$ -band profile reflectometer and associated with the edge harmonic oscillations, is shown in Fig. 1. A contour plot of the spatial location of scrape-off layer (SOL) density layers as a function of time is shown in Fig. 1(b) during EHO events, while a midplane magnetic probe signal is shown as an EHO timing reference in Fig. 1(a). In the contour plot, each individual profile was analyzed from a single full-band frequency sweep, so that there are 200 total profiles in 2 ms, equal to 10  $\mu$ s of temporal resolution.

Due to the high magnetic field (2 T), the  $X$ -mode  $Q$ -band profile reflectometer only can measure a density range of  $0\text{--}4.5 \times 10^{18} \text{ m}^{-3}$ . Thus, what we measured is the SOL density profile outside the separatrix. It is clear from Fig. 1 that the SOL density profile is modulated at the EHO fundamental frequency (about 6 kHz), corresponding well to the time history of the magnetic probe signal associated with the EHO as shown in Fig. 1(a). Some higher frequency components in the density profile perturbation may be due to the fact that the EHO is not a sinusoidal signal but has multiple harmonics, just like the magnetic signal in Fig. 1(a).

In order to test the density profile measurement quality, it is necessary to perform the same measurement during a plasma phase without EHO, as shown in Fig. 2. Figure 2(b) is the contour plot of the spatial location of the reflectometer density profile during a 3 ms time window during the ELM-free  $H$ -mode phase of the same discharge shown in Fig. 1. The absence of the EHO is indicated by the magnetic probe data in Fig. 2(a). The comparison data were obtained with

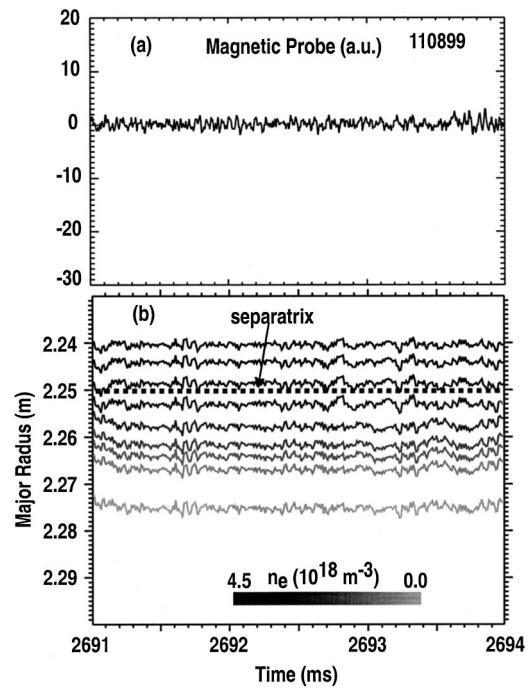


FIG. 2. For shot 110 899, (a) time history of the magnetic probe signal in ELM-free period with no EHO, and (b) the contour plot of the spatial location of reflectometer density layers as a function of time.

the same data acquisition analysis parameters as for Fig. 1. In Fig. 2(b), there are no large systematic profile variations, but only small fluctuations in this quiet plasma. The amplitude of the residual fluctuations is about 2 mm, similar to the result in  $L$ -mode plasma.<sup>10</sup> By contrast, the profile modulation generated by the EHO [Fig. 1(b)] is about 1 cm peak to peak, more than five times bigger than in the no EHO case.

#### IV. EDGE DENSITY PROFILE EVOLUTION DURING ELMs

The  $Q$ -band fast sweep reflectometer has also been employed to investigate ELMs in DIII-D. Edge localized modes (ELMs) are periodic relaxations of the edge pressure gradient in  $H$  mode,<sup>14,15</sup> resulting in pulses of energy and particles transported across the separatrix to the SOL and eventually into the divertor. Because an ELM deposits a large amount of energy on the target, it has been identified as a serious concern for the divertor of large tokamaks. ELMs also have the effect of limiting the edge pressure gradient, so the total confinement is affected by ELMs through changing the energy stored in the pedestal. Because of very fast profile variations during ELMs, profile reflectometer measurements with high resolution during ELM events are of interest.

Due to the fact that profile variations are larger during ELMs as compared to the EHO case, the range resolution filter bandwidth had to be set larger during automated analysis, allowing a large dynamic range for the extracted phases. For these data the full band sweep rate was 100  $\mu$ s, with a 10 MHz sampling rate and 1.5 s data coverage. Figure 3 demonstrates the high resolution edge density profile evolution during ELMs over a period of 200 ms, corresponding to 2000 profiles. In this plasma, the plasma current is 1.4 MA, and the toroidal magnetic field is 1.78 T. The measured den-

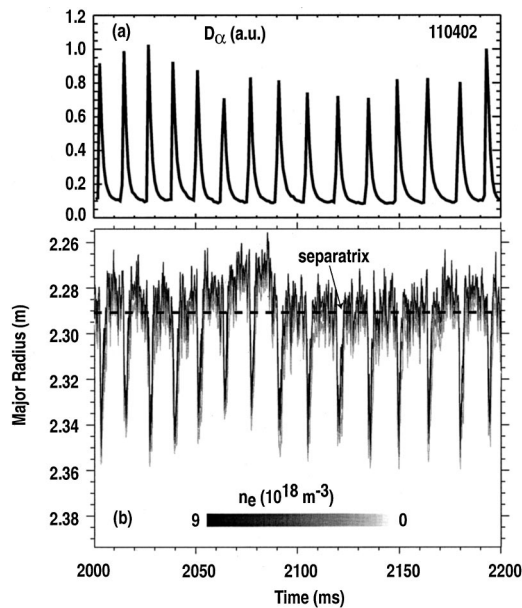


FIG. 3. For an ELMing plasma shot 110402, (a) time history of  $D_\alpha$  emission signal indicating the ELM events. (b) The contour plot of the spatial location of edge density layers as a function of time, as measured by  $Q$ -band reflectometer. A MHD event happens around 2086 ms.

sity range with the  $X$ -mode polarization reflectometer is from  $0$  to  $9 \times 10^{18} \text{ m}^{-3}$ , which covers from the SOL to inside the separatrix, whose radial location is  $2.29 \text{ m}$ . The  $L$ - $H$  transition occurred at  $1.1 \text{ s}$  after neutral beam injection heating. After a short (about  $50 \text{ ms}$ ) ELM-free period, the plasma entered a type 1 ELMing phase. The repetition period of the ELMs was about  $10 \text{ ms}$  as shown by the  $D_\alpha$  signal in Fig. 3(a). In Fig. 3, it is clear that the SOL density profile becomes broader at the onset of every ELM. The edge profile evolution is constant, except that the profile shifts inwards around  $2086 \text{ ms}$  when a MHD event happens.

In order to examine the fast time response more clearly, one ELM event is shown on a shorter time scale in Fig. 4. Unfortunately, the time resolution of the  $D_\alpha$  signal is not very high, only  $1 \text{ ms}$ . However, from Fig. 4(a), it is evident that the profile becomes broader within  $0.5 \text{ ms}$  when the ELM occurs, then relaxes back to a normal  $H$ -mode edge within  $2$  or  $3 \text{ ms}$ . Multiple sequential edge profiles over the period from  $2178$  to  $2184.5 \text{ ms}$  are presented in Fig. 4(c). The arrow lines indicate the time sequence. At the onset of the ELM the density profile expands outward to the vessel wall position. During the profile relaxation, the gradient in the SOL decreases first, then the density start position moves inwards until eventually the initial density profile is recovered. The pictures of the edge profile evolution during ELMs as measured by the reflectometer system are clear and reasonable.

## V. CONCLUSIONS

Multiple improvements to the DIII-D solid-state  $Q$ -band profile reflectometer system have resulted in a demonstrated ability to track localized time varying plasma instabilities. The improvements include the use of high performance digitizers, optimization of the microwave propagation polariza-

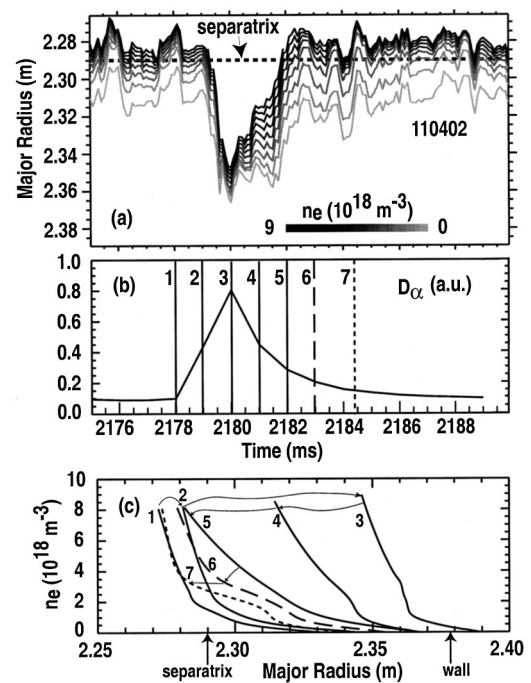


FIG. 4. For an ELMing plasma shot 110402, (a) the contour plot of the spatial location of edge density layers during a single ELM. (b)  $D_\alpha$  emission signal indicating ELM event timing. (c) The edge density profiles every  $1 \text{ ms}$  during the ELM. The labels of lines correspond to the time marks in (b).

tion, development of an improved automated criterion for detection of the plasma start position, and further optimization of the adaptive data smoothing and range resolution bandwidths. The improved capability of the system has been demonstrated with two examples. For the QDB plasma regime, it is observed that the density profile in the SOL is modulated by the EHO fundamental frequency. For ELMing plasmas, the fast reflectometer profile measurement provides high resolution profile evolution during ELMs. The SOL profile expands outward to the vessel wall at the onset of type I ELMs, indicating large changes in SOL transport.

## ACKNOWLEDGMENTS

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