Millimeter-wave Fast-sweep FM Reflectometry Applied to Plasma Density Profile Measurements

Kang Wook Kim

Abstract

A fast-sweep broadband FM reflectometer system has been successfully developed and operated at the DIII-D tokamak, producing reliable density profiles with excellent spatial ($\leq$ 1 cm) and temporal resolution (~100 μs). The system uses a solid-state microwave oscillator and an active quadrupler, covering full Q-band frequencies (33~50 GHz) and providing relatively high output power (20~60 mW). The system hardware allows fullband frequency sweep in 10 μs, but due to digitization rate limit on DIII-D, sweep time was limited to 75~100 μs. Fast frequency sweep has helped to reduce density fluctuation effects on the reflectometer phase measurements, thus improving reliability for individual sweeps. The fast-sweep system with high spatial and temporal resolution has allowed to measure fast-changing edge density profiles during plasma ELMs and L-H transitions, thus enabling fast-time scale physics studies.

Key words : millimeter-wave, FM reflectometry, FM radar, plasma diagnostics

Ⅰ. INTRODUCTION

The main advantages of the reflectometer system for plasma density profile measurements are as follows: 1) Reflectometry requires only minimal port-access, 2) it can be implemented with low-cost and flexible configurations, and 3) it can provide density profiles with high spatial and temporal resolution. Various reflectometer density profile systems have been developed and demonstrated on worldwide magnetic plasma confinement devices including DIII-D[1]~[4], TFTR[5], ASDEX[6], JET[7], RTP[8], etc. The major reflectometer techniques can be categorized by source modulation types: i.e., FM (frequency modulated)[1]~[4],[6], AM (amplitude modulated),[5] pulse reflectometer systems[8], ultrashort pulse radar,[9] and pulse compression radar[10]. While each technique has its intrinsic merits and disadvantages, all these techniques have demonstrated sub-cm spatial resolution with a metal mirror. However, for reliable density measurements with a turbulent a plasma, each system should be able to cope with strong density fluctuations, high dispersion, and spurious reflections. For example, to overcome density fluctuation effects with a plasma, an FM reflectometer is required to sweep frequency in a time scale faster than the phase velocity of local density fluctuations.[3] Also a proper data analysis technique is required to compensate the fluctuation effects.

This paper describes the new hardware, the analysis technique, and typical profile measurements of the reflectometer density profile system on DIII-D. Significant improvements in reflectometer profile measurements had been resulted by utilizing the digital complex demodulation (CDM) technique to improve phase measurements[2]. With the development of a new fast-sweep system utilizing solid-state microwave sources, the rf frequency was swept fullband in 100 μs (possible to sweep in 10 μs with a fast digitizer) without reset time. With help of an advanced analysis technique on DIII-D, the system has produced very reliable individual profiles, thus greatly increasing time resolution. This improvement enabled to study fast-time scale physics in plasmas such as density changes during ELMs and L-H transitions, and to provide accurate averaged density profiles for a fixed time period.

The rest of this paper is structured as follows: the principles of broadband FM reflectometry is described in Section Ⅱ. Hardware description of the fast-sweep broadband FM reflectometer installed on DIII-D is presented in Section Ⅲ, followed by the optimal data analysis considerations in Section Ⅳ. And typical density profile measurements using the fast-sweep reflectometer are presented in Section Ⅴ. Finally the paper is concluded in Section Ⅵ.

Ⅱ. PRINCIPLES OF BROADBAND FM REFLECTOMETRY

A broadband FM reflectometer measures the phase delay of the reflected electromagnetic wave as an rf source is swept in frequency. The schematic of a broadband FM radar/reflectometer is shown in Fig. 1(a). With a metal mirror as a target, all the

Manuscript received January 26, 2001; revised March 3, 2001.
Kang-Wook Kim is with the Narda DBS Microwave - an L-3 Communications Company, 4805 Golden Foothill Parkway, El Dorado Hills, CA 95762
Work: (916) 939-7545, E-mail: Kang Kim@L-3com.com

frequency components of the launched wave will be reflected from the mirror located at fixed distance R. Since the phase shift of the reflected wave propagated through air is a linear function of the probing frequency f (i.e., $\Phi_v = (4\pi Rf)/c$), a beat signal with a constant frequency is produced in the mixer output if the rf frequency is swept linearly. The beat frequency (f_b) is proportional to the target distance (R) with a linear sweep; i.e.,

$$f_b = \frac{1}{2\pi}\frac{d\Phi_v}{dt} = \frac{2R}{c}\frac{df}{dt} \quad (1)$$

as shown in Fig. 1(b). However, if an EM wave is launched into plasmas, different frequency components of the probing wave is reflected from different spatial locations from the plasma (i.e., time varying R), thus producing time-varying beat frequency. The phase shift of the reflected wave from a plasma, $\Phi_p(f)$, is expressed as

$$\Phi_p(f) = \frac{4\pi f}{c}\int_{r_c(f)}^{r_p}\mu(r, f)dr - \frac{\pi}{2} \quad (2)$$

where $\mu(r, f)$ is the refractive index of the plasma, r_p the plasma start position, and $r_c(f)$ the cutoff layer for the probing frequency f. By measuring the phase delay of the reflected wave, a density profile can be reconstructed by numerically inverting (2)[3].

The total phase shifts extracted from the reflected signal of the reflectometer can be decomposed into three components:

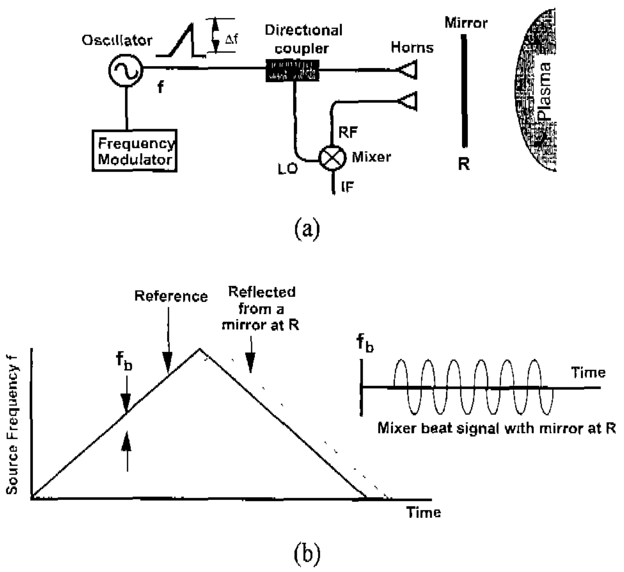

Fig. 1. (a) Schematic of a broadband FM radar/reflectometer. (b) With a mirror as a target, a beat signal with a constant frequency is generated in the mixer, where the beat frequency is proportional to the mirror distance R.

phase shifts due to waveguide (Φ_{WG}), air (Φ_{Vac}), and plasma (Φ_p) (i.e., $\Phi_{IF} = \Phi_{WG} + \Phi_{Vac} + \Phi_p$). The air and waveguide phase shifts should be subtracted from the total phase through a calibration process, which results in the desired plasma phase Φ_p for the profile inversion to obtain plasma density profiles.

Ⅲ. FAST-SWEEP FM REFLECTOMETER SYSTEM ON DIII-D

The schematic of the new fast-sweep FM reflectometer system on DIII-D is shown in Fig. 2. The system uses an 8∼12.5 GHz solid-state microwave source (HTO, hyper-abrupt varactor tuned oscillator) followed by an active frequency quadrupler to cover the full Q-band frequency range (32∼50 GHz) with relatively high output power 20∼60 mW. The system allows fullband frequency sweep in every 10 μs, which is considered as a sufficient sweep speed to effectively avoid density fluctuation effects for all plasma conditions[3]. For the data presented in this paper, the sweep rate was limited to 75∼100 μs due to the digitization rate limitation (maximum at 5 MHz) on DIII-D. The new hardware has successfully replaced the Backward Wave Oscillator (BWO)-based reflectometer system[4], which allowed only slow frequency sweeps with long reset time.

In order to stabilize frequency and to improve output power, the HTO and frequency quadrupler were actively cooled to maintain at a constant temperature using thermo-electric coolers. This helped to confine frequency uncertainty within 30 MHz. Because the output frequency from the HTO driven by a linear voltage sweep was highly nonlinear, an arbitrary function generator was used to linearize the output frequency. To obtain the necessary sweep voltage waveform for linearization, frequency calibration data were inverted and then loaded into an arbitrary function generator. In Fig. 3(a) and (b), a mixer beat signal obtained with the linear voltage sweep was compared with a signal driven by the frequency linearizing voltage sweep shown in Fig. 3(c). In this test, a metal mirror was used as a target, and a nearly constant frequency beat signal (as shown in Fig. 3(b)) proved linearization of the output frequency.

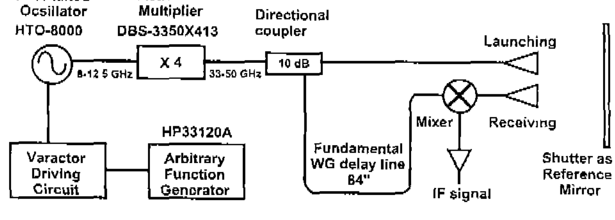

Fig. 2. Schematic of the new fast-sweep FM reflectometer on DIII-D.

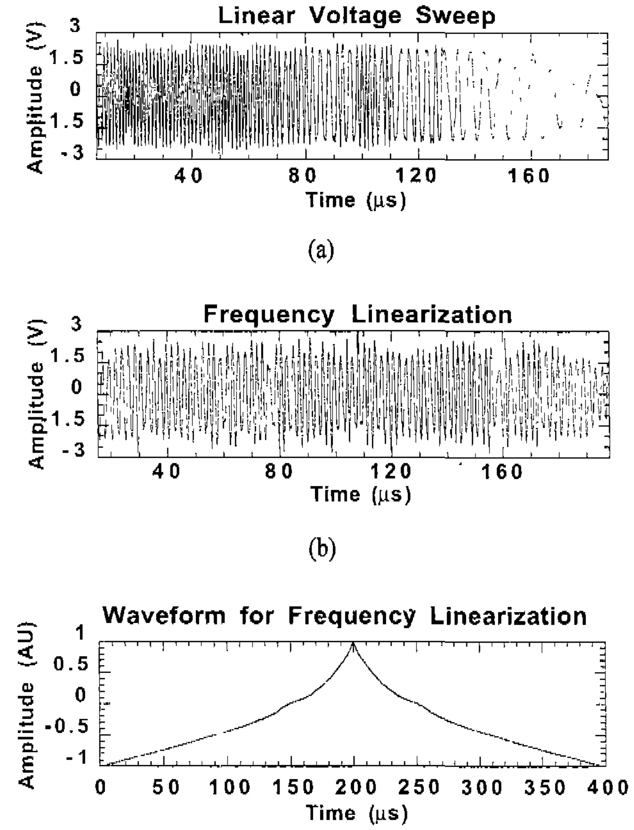

Fig. 3. With a mirror as a target, (a) a mixer beat signal obtained by a linear voltage sweep, (b) a beat signal driven by a frequency linearizing waveform as shown in (c).

Ⅳ. DATA ANALYSIS CONSIDERATIONS

When launched wave is reflected from plasmas, time-varying mixer IF signal is obtained. In order to extract the phase delay accurately, the digital complex demodulation technique (CDM) has been employed[2]. The CDM, which is equivalent to analog heterodyne quadrature detection, simultaneously extracts phase and amplitude of the reflected wave. This technique has improved the extracted phase accuracy ($\leq \pi/10$) as compared to the conventional fringe counting method, thereby improving the reconstructed density profiles. In addition, fast sweeping of the launched rf sources has enabled to obtain cleaner the mixer IF signal in the presence of plasma density fluctuations, resulting in more reliable individual profiles[3].

In measuring density profiles, reflectometer basically utilizes radar concepts, as target being dispersive plasma medium. In designing radar system, important system design parameters are *range resolution* and *precision,* which depend on the measurement bandwidth. The understanding of those parameters is critical for optimum reflectometer system design and improves the data analysis in reflectometer density measurements[11]. The *range resolution* is the minimum distance that can differentiate a real target from a false target such as reflections from window which typically are present in a reflectometer measurement. In broadband FM reflectometry, the signals from spurious reflections can be removed by filtering or spectral analysis. The *precision* is a measure of variations under fixed conditions. The precision can be improved by data smoothing with proper bandwidth, but too much smoothing can smear profile structures.

With a metal target, both the range resolution and the precision can be improved with more measurement bandwidth. However, in the case of a dispersive plasma, a new parameter, "*spatial sampling*", which determines the number of independent data used for density inversion or the effective number of measurement channels, becomes important. If too few channels are used, the density structures become aliased. Therefore data analysis should be performed to optimize the above mentioned three parameters: the range resolution, precision and spatial sampling. This optimal data processing technique was integrated in the analysis software for the new reflectometer system.

Ⅴ. DENSITY PROFILE MEASUREMENTS

The new fast-sweep FM reflectometer system has improved the density profile measurements through the new hardware and the advanced analysis technique. In a plasma discharge on DIII-D, reliable 1000 profiles have been produced by digitizing the mixer beat signal at 5 MHz rate with 1 MByte digitizer memory.

The new reflectometer enabled to study density profile changes which occur in a fast time scale at various phases of plasma confinements. One of these examples is the plasma transition from the low confinement mode (L-mode) to the high confinement mode (H-mode) in magnetic plasma confinement devices. This phenomena accompany a set of common features such as the formation of transport barrier at the plasma edge where density and temperature steepen after the transition, and a drop in the D_α radiation indicating significant decrease in the particle flux[12]. In addition, density fluctuation amplitude decreases at the transport barrier region.

Fig. 4(a) and (b) show the surface and contour plots of the edge density profile evolution across L-H transition. The measured density profiles are mainly outside the magnetic separatrix which is located at major radius 2.28 ± 0.01 m. In analyzing the density profiles with FM reflectometer, phase-delay measurements from two consecutive 100 μs frequency sweeps were averaged for better accuracy, plotting profiles every 200 μs. In the L-mode, the density slope is less steep around the separatrix than that of H-mode profiles, and profiles show

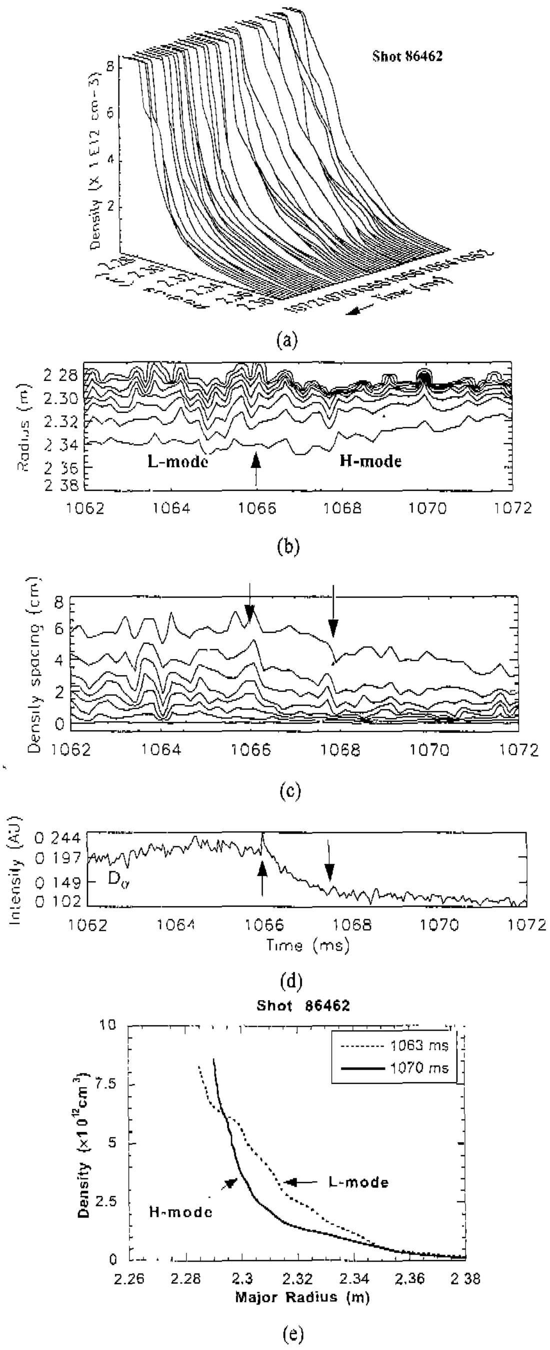

Fig. 4. Edge density profile evolution across the L-H transition, (a) surface graphics of density profiles where the plateau represents the maximum density measured, (b) contour plots where constant density lines are 1, 2, ⋯ 7, 8×10^{18} m^{-3} from the bottom, (c) density spacing between constant densities (1, 2, ⋯ 7 $\times10^{18}$ m^{-3}) and the maximum density (8×10^{18} m^{-3}), where upper lines are lower densities, (d) photodiode signal (D_α signal), (e) density profile slices during L-mode and H-mode.

several density fluctuation structures. After the transition to H-mode, the profile steepens around the separatrix location indicating the transport barrier formation. In the H-mode the mixer beat signal in FM reflectometer becomes very clean, which is consistent with the density fluctuation reduction. To better illustrate the profile shape changes, the radial spacing between discrete densities (1,2, ⋯, 7×10^{12} cm^{-3}) and maximum measured density 8×10^{12} cm^{-3} were plotted in Fig. 4(c). In the figure, if spacing between constant density lines is small, that region indicates steep density gradient, and if spacing between the lines is large, it indicates less steep density slope. Note that profile slope changes are more clearly observed in the density spacing plot (i.e., Fig. 4(c)) as compared to the density contours (i.e., Fig. 4(b)). The spacing between constant densities begin to change as synchronous with the drop of D_α signal in Fig. 4(d). During the transition to H-mode, the steepening of densities greater than 5×10^{12} cm^{-3} is completed in less than 1 ms, but the lower densities ($\leq3\times10^{12}$ cm^{-3}) took about 2 ms for the completion of transition, indicating that steepening begins from higher density region and then extending to lower densities. The D_α signal, which is roughly proportional to the particle outflux, is seen to be closely correlated with the edge density profile changes; i.e., D_α signal dropping for this shot was about 1.5 ms which is of the same time scale of edge density changes. Fig. 4(e) shows slices of density profiles in L-mode and H-mode, showing much steeper density gradient in H-mode at around the separatrix as compared to L-mode. The scrape-off edge density outside the separatrix in the H-mode becomes further reduced as the H-mode develops.

Another interesting phenomenon happening in a magnetically confined plasmas is an edge localized mode (ELM). During an H-mode phase, periodic and fast energy and particle losses may occur localized at the plasma edge, thus named as edge localized modes (ELMs).[13] ELMs degrade time averaged global confinement time, but can be used for regulating density and impurities, which enabling operation of a quasi-stationary plasma. Fig. 5(a) and (b) shows surface and contour plots of dramatic edge density profile changes during a giant ELM on DIII-D. Before ELM occurs, H-mode profiles maintain steep density gradient at the transport barrier. But with an ELM, sudden burst of density occurs within 100 μs, after which profile slowly returns to H-mode on a time scale of 10~15 ms.

Ⅵ. CONCLUSION

A highly reliable, fast-sweep broadband FM reflectometer for density profile measurements has been demonstrated at the DIII-D tokamak. In this paper, the principles of the broadband FM reflectometry, the improved system hardware, and data analysis technique as well as measured results are described.

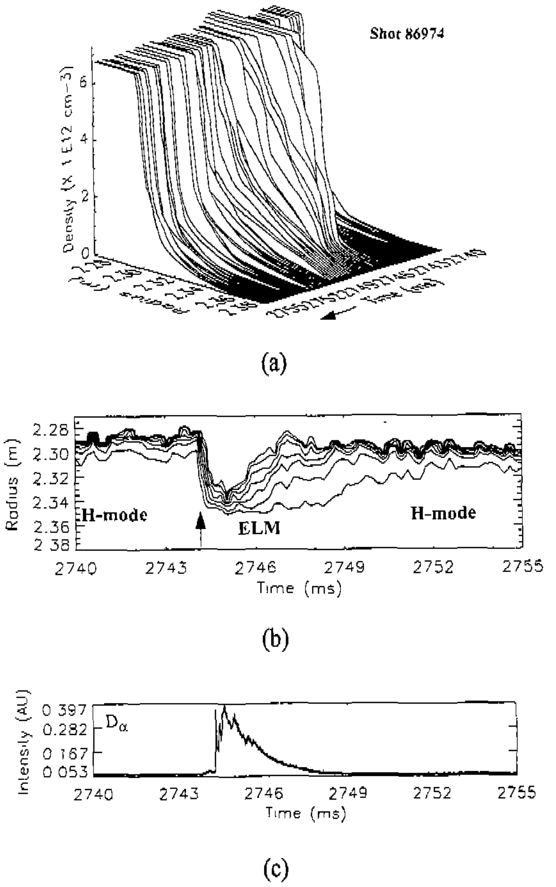

Fig. 5. Edge density profile changes with a giant ELM (profiles in every 200 μs), (a) surface graphics of density profiles, (b) contour plots where constant density lines are 1, 2, $\cdots$ 6, 6.5×10^{18} m^{-3} from the bottom, (c) photo-diode signal.

The new reflectometer system using solid-state sources has provided many advantages over the old BWO-based system:[4] i.e., improved reliability, faster frequency sweep, compactness, etc. With fast profile measurements and improved data analysis, the new system enabled to observe fast-changing density profiles during ELMs and L-H transitions. The fast changing density profile measurements in these plasma phenomena agreed with other diagnostic indicators, and also revealed the detailed profile evolution during these periods.

REFERENCES

[1] K. W. Kim, et al., "Development of a fast solid-state high-resolution density profile reflectometer system on DIII-D", *Rev. Sci. Instrum.*, 68(1), pp. 466-9, 1997.

[2] K. W. Kim, et al., "Advances in reflectometric density profile measurements on the DIII-D tokamak", *Rev. Sci. Instrum.*, 66(2), 1229, 1995.

[3] K. W. Kim, "High-resolution Millimeter-wave Reflectometry for Electron Density Profile Measurements in Tokamak Plasmas", *Ph.D. Dissertation, University of California*, Los Angeles, July 1996.

[4] E. J. Doyle, et al., "X-mode broadband reflectometric density profile measurements on DIII-D", *Rev. Sci. Instrum.*, 61(10), 2896 (1990).

[5] G. R. Hanson, et al., "Differential-phase reflectometry for edge profile measurements on Tokamak fusion test reactor", *Rev. Sci. Instrum.*, 66(1), 863 (1995).

[6] M. E. Manso, "Reflectometry in Fusion devices", *Plasma Phys. Control. Fusion,* 35, B141 (1993).

[7] A. C. C. Sips, et al., "Analysis of reflectometry density profile measurements in JET", *Plasma Phys. Control. Fusion,* 35, 743-755 (1993).

[8] S. H. Heijnen, et al., "Density perturbation studies by means of pulsed radar reflectometry", *Rev. Sci. Instrum,* 66(1), 419 (1995).

[9] C. Domier, et al., "Ultrashort-pulse reflectometry", *Rev. Sci. Instrum.*, 66(1), 399 (1995).

[10] C. Laviron, et al., "First experiments of pulse compression radar reflectometry for density measurements on JET plasmas", *Plasma Phys. Control. Fusion*, 37, 975 (1995).

[11] E. J. Doyle, et al., Reflectometry Applications to ITER, in "*Diagnostics for Experimental Thermonuclear Fusion Reactors*", (P.E. Stott, G. Gorini, and E. Sindoni, eds.), pp. 117-132, Plenum Publishing Corp., New York, 1996.

[12] K. H. Burrell, "Observation of an improved energy-confinement regime in neutral-beam-heated divertor discharges in the DIII-D tokamak", *Phys. Rev. Lett.,* 59(13), 1432 (1987).

[13] H. Zohm, et al., "ELM studies on DIII-D and a comparison with ASDEX results", *Nuclear Fusion,* 35, 543 (1995).

Kang Wook Kim

received B.S. and M.S. degrees in electrical engineering from Seoul National University in 1985 and 1987, respectively. In 1996, he received Ph.D. degree from the University of California, Los Angeles.

From 1987 to 1990, he worked as a researcher at the Korea Electrotechnology Research Institute, Changwon. From 1996 to 1998, he held a position as a post-doctoral researcher at the University of California, Los Angeles. From 1998 to 1999, he was employed as a microwave design engineer at P-Com, Inc., Campbell, California, designing commercial transceivers for digital microwave radios. Since 1999, he has been working as an RF design engineer at Narda DBS Microwave, an L-3 Communications Company, USA. He is currently engaged in research and development of microwave/mm-wave components and sub-systems for wireless and fiber optic communications. His research interests include antennas for wireless personal communications, EM interactions between human body and antennas, and plasma diagnostics using microwave/mm-wave components.