Recent progress with high-resolution FM profile reflectometer measurements on DIII-D

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Abstract

Hardware and software advances continue to be incorporated in the high-resolution FM-CW density profile reflectometry system on DIII-D. A novel dual-polarization measurement technique was utilized, to expand the density coverage 0-6.4x10^{19} m^{-3} continuous, and with a time resolution of \geq 10 \mu s and spatial resolution of \geq 4 mm. The high memory-depth PC-based data-acquisition system has been expanded to 6 digitized channels. A new between-shot automatic profile analysis capability has recently been implemented, taking 4-5 minutes to automatically analyze X-mode profiles between discharges and storing profiles into the DIII-D MDSplus database. System capabilities are illustrated using results from a variety of areas such as L-H transition and pedestal physics, ELM dynamics, plasma-wall interaction studies, disruptions and ITB studies.

1. Introduction

Profile reflectometry has been widely used in fusion study for density profile measurement, and is planned for profile measurement as well as edge location control on ITER. Because of its high time and spatial resolution, it is also successfully employed to investigate some plasma MHD instabilities [1,2], as well as edge localized modes (ELMs). Currently, the major emphasis of work with the high-resolution FM profile reflectometer system on DIII-D has transitioned from development of the hardware and measurement capabilities to physics utilization. Despite this change in emphasis, both hardware and software advances continue to be incorporated in the system. These advances include a full solid state system, simultaneous O/X- mode launch,

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increased fast digitizing capability, and a new between-shots automatic profile analysis. These advances are described in detail below.

2. System Hardware Upgrades: Dual-polarization Technique
Since the IRW6 meeting in May 2003, a novel dual-polarization measurement technique has been utilized in our profile reflectometry system, in which O- and X-mode polarizations are simultaneously launched from a common solid-state microwave source. In addition, the frequency coverage has been expanded from Q-band (32-50 GHz) to V-band (50-72 GHz) [3]. This increase in frequency coverage (using high performance solid-state microwave sources) has expanded the density coverage from 0-3.1x10^{19} m^{-3} in 2003 [4], with an unmeasured gap, to 0-6.4x10^{19} m^{-3} continuous. The system now possesses good time (\geq 10 \mu s) and spatial resolution (~ 4 mm). The system consists of two sub-systems (Q-band and V-band). A schematic of one sub-system is shown in Figure 1. The probe microwave beams are generated by a solid-state source which can sweep full frequency band in as little as 10 \mu s, and which is launched at 45^0 polarization into the plasma. This serves to couple to both O- and X-mode waves. Microwaves are simultaneously reflected from both the X-mode right hand cutoff frequency layer and the O-mode electron plasma frequency layer. Simultaneously, the reflected O- and X-mode waves are received by the two orthogonal horns, and mixed with local beams separately. With this approach, the range in density that can be measured is expanded.

![Figure 1 a schematic of profile reflectometry system on DIII-D](image)

3. Analysis Improvements and X-mode Profile Between-shots Analysis
The data acquisition system has been upgraded by using three high memory-depth Gage CS 12100 PC-based data acquisition boards, with high sampling rate (50 MHz in dual-channel mode) and with large on-board memory (512 MB/board, maximum total 1.5GB/shot). This high performance system can be operated either in continuous digitization for a maximum 2.56 s data coverage at 50 MHz, or in “Burst” data acquisition mode with ~ 1 ms duration data bursts every 5-10 ms for up to 6 s.

In order to quickly analyze the large volume of data, a between-shot profile analysis capability has been implemented. The new analysis is based on a previous analysis program, employing digital complex demodulation (CDM) [5] and other techniques [6]. By simultaneously using ten Linux-based computers (Dual-Xeon 2.66 GHz processors, 2 GB RAM each), analysis of X-mode profiles every 5-10 ms throughout the whole discharge takes 4-5 minutes, completing well before the next discharge. Profile data is stored in the DIII-D MDSplus database and is ready for viewing between-shots after ~ 10 minutes. An example of between-shots X-mode profile analysis is shown in Figure 2. The density contours (total of 800 profiles), with 4 s data coverage and 5 ms time resolution, are shown in Figure 2(a), where the color curves represent different density layers. It is clearly observed that the inner density layers move inward during the application of electron cyclotron current drive (ECCD) and during locked modes occur later. The measured density decreases are consistent with the CO$_2$ line average density measurement shown in Figure 2(b).

![Figure 2](image_url)

Figure 2, an example of between-shot profile analysis, reflectometer density contours (a), and line average density (b)
4. Comparison Between Diagnostics and an Example of Selected Physics Applications

Currently, the physics applications of profile reflectometer measurements include plasma-wall interaction studies, ELM dynamics, L-H transition and pedestal evolution. In plasma-wall interaction studies, good agreement in the edge density profile is found between different diagnostics on DIII-D as shown in Figure 3, where the black circles are Thomson scattering data, the red squares are Langmuir probe data and blue diamonds represent reflectometer profile measurements for shot 120350 at 4150 ms.

![Figure 3](image)

Figure 3, edge profile measurement comparison among reflectometer, Langmuir probe and Thomson scattering

A detailed example of the density profile dynamic evolution through a single Type-I ELM is shown in Fig. 4. The ELM timing is shown by a divertor $D_\alpha$ signal, Fig. 4(a), where the numbers and vertical lines represent the times for the density profile sequence shown in Fig. 4(b). In Fig. 4(b), profile 1 is taken just before the ELM onset, and shows a typical H-mode edge pedestal with steep gradient. At the onset of the ELM, profile 2 shows an increase in SOL density, with the density at the top of the pedestal slightly reduced. At the time of the ELM crash (profile 3), about 100 µs later, the SOL profile has expanded radially outward to the vessel wall, where there is a relatively large density rise of $\sim 2 \times 10^{18}$ m$^{-3}$. During the recovery phase, profile 4 shows the pedestal gradually rebuilding, and SOL density reducing. The final profile in the sequence, 5, shows a return to a well-defined edge pedestal several ms after the ELM onset. Thomson scattering data obtained at the same time as reflectometer profile 5 are shown via points with error bars, showing good agreement.
between the two measurements. The illustrated evolution of the pedestal and SOL density profiles demonstrates that the density rise observed in the SOL is directly linked to the pedestal loss during the ELM.

Figure 4, (a) Dα signal with times for (b) indicated and (b) density profile dynamic evolution through a single Type-I ELM for shot 118219.

5. Summary
Both hardware and software upgrades continue to be incorporated in the DIII-D FM density profile reflectometer system. The density coverage has been expanded, 0-6.4x10^{19} m^{-3}, using simultaneous dual polarization launch. New between-shot profile analysis capability has been implemented, and X-mode profiles are stored in an MDSplus database. The increased system capability has expanded the range of physics issues which can be addressed, e.g. plasma-wall interaction studies, ELM dynamics, L-H transition and pedestal evolution.

References