Improved reflectometer electron density profile measurements on DIII-D

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Details are presented of recent improvements to hardware and analysis code components of the DIII-D density profile reflectometer system. The improvements to the hardware increased the system signal-to-noise ratio and reduced spurious reflections. An improved automated method has been developed to accurately determine the zero density plasma start position. With these improvements the uncertainty in the zero density plasma start position is reduced from ~7 to ~2 mm, the position uncertainty with a fixed mirror target is reduced from ~4 to ~2 mm, and the time resolution is improved to 10 μs (previously ~100 μs). © 2003 American Institute of Physics.

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I. INTRODUCTION

Reflectometry has been widely pursued for electron density profile measurements in worldwide fusion devices due to its attractive intrinsic merits: minimal access requirements, high spatial and time resolution, low cost and hardware flexibility, and no symmetry assumption required for profile inversion, etc.1–3 Since the 1990s, UCLA has been developing a continuous frequency-modulated (FM) reflectometer system on DIII-D to provide edge and core electron density profiles with high temporal and spatial resolution in support of physics research. Results over the years on DIII-D,4–9 and from other large devices like ASDEX Upgrade,10 Joint European Torus, 11 and Tore Supra12 have demonstrated the ability of using reflectometry as a standard density profile diagnostic for future fusion devices like ITER.13 Due to its high sensitivity, it is a summary.

II. DIAGNOSTIC DESCRIPTION

The UCLA reflectometer profile system on DIII-D4–9 consists of two continuous broadband FM subsystems. One is a high performance solid-state Q-band system, composed of an 8–12.5 GHz hyperabrupt varactor-tuned oscillator (HTO) and an active frequency quadrupler to give a 32–50 GHz output. The full band sweep time of this subsystem is now ≥10 μs. The other subsystem is a backward wave oscillator-based reflectometer with frequency range of 50–75 GHz, measuring a profile in 400–600 μs, but with dwell time of ~2.5 ms. The operating polarization of both systems can be chosen on a day-to-day basis to optimize spatial and density coverage in line with experimental needs.9 With O-mode operation (E∥B), they cover a density range of 1.4–7.2×10¹⁹ m⁻³ from edge to core region, while X-mode operation (E⊥B) covers 0–3×10¹⁹ m⁻³ (the maximum measurable density depends on magnetic field), for scrape-off layer (SOL) and low density region measurements. A PC-based data acquisition system is employed for flexible continuous or multi-burst sampling. Typically, a total of 1 s of data per shot can be recorded at a 10 MHz sampling rate, e.g., 10 000 profiles per shot for 100 μs sweeping time with the Q-band system. Figure 1 is a schematic diagram of the broadband FM reflectometer system hardware on DIII-D. The rf source frequency is swept as a function of time, gen-

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FIG. 1. Schematic diagram of the broadband FM reflectometer system hardware on DIII-D.
operating an intermediate frequency (IF) signal at the mixer due to the different propagation lengths in the rf and LO legs. The rf waves are launched into the plasma, and reflect back from one or more plasma cutoff layers. By measuring the plasma phase delay for a range of probing frequencies, which are reflected at different radii, the plasma electron density profile as a function of radius can be recovered using an inversion procedure. Digital complex demodulation is used to extract the phase information from the IF signal, i.e., mixer output. As profile reflectometer systems are in nature specialized close range radar systems, radar-like software-based data processing techniques are employed, including consideration of factors such as range resolution, and precision bandwidth, etc. Adaptive data processing is implemented to cope with time and spatially varying density gradients. In this article, we describe how our previous analysis package (implemented in IDL) is further extended using an improved automated criterion to determine the zero density plasma start position more precisely. As a result of these improvements, our system can now achieve an uncertainty in the zero density plasma start position of ~2 mm, comparable to the position uncertainty with fixed mirror target, and a time resolution of 10 μs.

III. IMPROVEMENTS TO HARDWARE

Reliable density profile measurements with simultaneous sub-cm spatial and 100 μs temporal resolution were previously demonstrated on DIII-D. By making use of the full capabilities of the PC-based data acquisition system, i.e., dual-channel digitization at a 50 MHz sampling rate, and hardware improvements described here, the system full band sweep time has been reduced to 10 μs. Several improvements have been implemented to increase the system’s signal-to-noise ratio at high sweep rates. The frequency sweep circuit for driving the HTO was modified to decrease the noise in the sweeping voltage from 10 mV, thus decreasing the source frequency jitter from ~30 to ~10 MHz at the output. This modification also changed the circuit feedback system, suppressing spurious high frequency components in the signal. These changes increased the system signal-to-noise ratio by a factor of 2–3. In addition, the operating point of the balanced mixer was optimized by adjusting the LO power so as to reduce spurious signals generated by LO feedthrough. The total improvement of the system signal-to-noise ratio is greater than 4.

Another improvement is the optimization of the angles of the launch and receive horns to both maximize the signal from the desired plasma cutoff and reduce reflections from unwanted cutoffs. There are three kinds of plasma cutoff layers that can reflect the launched rf waves: X-mode left-hand (f_LH) and right-hand (f_RH) cutoff layers, and the O-mode cutoff layer (f_pe). The X-mode cutoff frequencies are

\[ f_x = \pm \frac{f_{ce}}{2} + \sqrt{f_x^2 + \frac{f_{ce}^2}{4}}, \]

where \( f_{ce} \) is electron cyclotron frequency.

FIG. 2. Raw IF signals as a function of rf frequency for two cases: (a) horn angles matched to magnetic field pitch angle, and (b) horn mismatched by 25°.

\[ f_{pe} = \frac{1}{2 \pi} \sqrt{\frac{c^2 n_e}{\varepsilon_0 m_e}} \]

is the cutoff frequency for O-mode propagation, and \( f_{LH} \) and \( f_{RH} \) are \( f_x \) with “−” and “+” in the formula, respectively. Note that \( f_{LH} \) and \( f_{pe} \) have zero frequency at zero density, while \( f_{RH} \) equals \( f_{ce} \) at zero density. Using right-hand cutoff \( f_{RH} \) the entire edge density profile can be measured from zero density, and the location of the edge zero plasma density layer can be identified from the change in IF signal as the rf frequency is swept across \( f_{RH} \) (or \( f_{ce} \)). However, the toroidal magnetic field and plasma current directions can change from experiment to experiment on DIII-D. If the launch and receive antenna angles do not match the magnetic field pitch angle at the plasma edge, more unwanted O-mode reflection and less reflection from X-mode cutoff layers can be expected.

On DIII-D, we have had the ability to rotate the launch and receive antennas to vary the operating polarization on a day-to-day basis for several years. More recently, we have implemented the capability to more accurately adjust the antenna angles to cater to changes in toroidal magnetic field and plasma current directions. Plotted in Fig. 2 are the raw IF signals versus rf frequency for two cases; (a) a matched pitch angle case, and (b) a mismatched case. In the case of Fig. 2(a) the launch and receive horn angles (~12°) were very well aligned to the edge magnetic pitch angle at radii of 2.3–2.4 m (~11.6°–12°). By contrast, in the case of Fig. 2(b) the launch and receive horns were misaligned by ~25° from the edge magnetic pitch angle (~13°).
strate the benefit of accurate antenna alignment to the magnetic field pitch angle.

IV. IMPROVEMENTS IN DATA PROCESSING

Using X-mode propagation on DIII-D, precisely determining the location of the zero density plasma start position is a critical first step to a reliable, accurate density profile measurement, since the density inversion is done from this point inward. Our previous software package (implemented in IDL) is further extended using an improved automated criterion to determine the zero density plasma start position more precisely. References 12 and 5 have shown cases where a very clear rise of the IF signal can be identified as the start of \( f_{\text{RH}} \) cutoff. However, in general, varying plasma conditions results in a number of ways in which the \( f_{\text{RH}} \) signal starts relative to the other plasma cutoff layers, which makes automatic identification of the plasma start for all cases a challenge. Here we describe and illustrate the use and implementation of the automated method to determine the plasma start under all these cases.

Shown in Fig. 3 are plots of \( f_{\text{LH}} \), \( f_{\text{RH}} \), and \( f_{\text{pe}} \) versus radius for three indicative cases on DIII-D: (a) Low density, such that \( f_{\text{LH}} \) is always below \( f_{\text{ce}} \) and \( f_{\text{RH}} \), (b) medium density, such that \( f_{\text{LH}} \) is higher. (Here the launched waves at rf frequencies below \( f_{\text{RH}} \) reflect from \( f_{\text{RH}} \) at some distance inside the plasma edge before transitioning to \( f_{\text{RH}} \) as the rf frequency is swept higher), and (c) a high density H-mode edge, which is very common on DIII-D. In this case the launched rf waves first reflect from \( f_{\text{LH}} \) close to the plasma edge before transitioning to \( f_{\text{RH}} \).

FIG. 3. Plots of cutoff frequencies \( f_{\text{LH}} \), \( f_{\text{RH}} \), and \( f_{\text{pe}} \) vs radius for three indicative cases on DIII-D: (a) Low density, such that \( f_{\text{LH}} \) is always below \( f_{\text{ce}} \) and \( f_{\text{RH}} \), (b) medium density, such that \( f_{\text{LH}} \) is higher. (Here the launched waves at rf frequencies below \( f_{\text{RH}} \) reflect from \( f_{\text{RH}} \) at some distance inside the plasma edge before transitioning to \( f_{\text{RH}} \) as the rf frequency is swept higher), and (c) a high density H-mode edge, which is very common on DIII-D. In this case the launched rf waves first reflect from \( f_{\text{LH}} \) close to the plasma edge before transitioning to \( f_{\text{RH}} \).

FIG. 4. Three signals: (a) raw IF signal vs rf frequency, (b) selected frequency range with bandpass filtering, and (c) smoothed and squared signal. These signals are shown for four cases: (i) low density, corresponding to Fig. 3(a), (ii) medium density, corresponding to Fig. 3(b), (iii) high density, corresponding to Fig. 3(c), and (iv) high density with antenna angles mismatched to the magnetic field pitch angle corresponding to case shown in Fig. 2(b).
rium solver) to select the frequency range from \( f_{\text{ce}} \) at the vessel wall (\( f_{\text{wall}} \)) to \( f_{\text{ce}} \) at the separatrix (\( f_{\text{sept}} \)). At this point a rough estimate of \( f_{\text{start}} \) is made by determining the location of largest rise in signal amplitude between \( f_{\text{wall}} \) and \( f_{\text{sept}} \). The selected range is then bandpass filtered; the filter center frequency is taken as the average IF frequency in the range from the estimated \( f_{\text{start}} \) to \( f_{\text{sept}} \) while the frequency width is taken to be the same as the rms frequency width of the signal spectrum. This selected and filtered frequency range is shown as plot (b) in each of the four major panels of Fig. 4. The next step in the automated detection of \( f_{\text{start}} \) is to form the smoothed square of the selected and filtered frequency range, as shown in plot (c) in Fig. 4. The maximum smoothed square signal value \( P_{\text{max}} \) is found and then the first frequency below that whose smoothed square signal is \( \approx (0.02 \times P_{\text{max}} + \text{minimum smoothed square signal}) \) is chosen as the final \( f_{\text{start}} \).

As can be seen, the processed signal, (c), for the first three cases (panels i–iii) has a clear transition to reflection from \( f_{\text{RH}} \), much clearer than the original raw signal counterpart in (a). Even the final and most difficult case, Fig. 4 iv, which has high density such that \( f_{\text{LH}} \) and \( f_{\text{RH}} \) are close together, combined with antennas that are mismatched to the magnetic field pitch angle, has a reasonably unambiguous transition to reflection from \( f_{\text{RH}} \). In practice, the automated criterion is reliable and has proven superior to other criteria previously used and tested for the same purpose. These other methods to determine the plasma start frequency included a test for a phase/time delay change, and a simpler amplitude change test. After obtaining \( f_{\text{start}} \), the zero density plasma start position is directly calculated as the position where \( f_{\text{ce}} \) (\( f_{\text{ce}} \) spatial distribution is acquired from EFIT) since \( f_{\text{RH}} \) equals \( f_{\text{ce}} \) at zero density. It should be noted that this technique to obtain the plasma start position does not utilize the radar ranging capability/data processing features of the reflectometer system.

V. RESULTS

To quantitatively assess the profile reflectometer system’s improved spatial accuracy we selected a plasma discharge in which the edge region did not experience obvious movement due to large magnetohydrodynamic (MHD) activity or other physics processes, a so-called “simple-as-possible plasma” (SAPP) stationary \( L \)-mode experiment.\(^{17}\) Shown in Fig. 5(a) is the measured zero density plasma start position as a function of time from such a discharge. The data shown were taken with 100 \( \mu \text{s} \) time resolution, i.e., there are 125 data points in the 12.5 ms time window shown. As can be seen, the data are very reproducible; statistical analysis shows that the standard deviation in the plasma starting position is only 2 mm, while the corresponding standard deviation in \( f_{\text{start}} \) is 38 MHz. The standard deviation in the plasma start position was \( \sim 7 \) mm before the implementation of the improvements reported in this article. It should be noted that the variation in the position measurement comes from several factors, including hardware and software uncertainties as well as actual plasma variations due to turbulence, resonance absorption at the upper hybrid layer (the Budden tunneling effect\(^{18}\)), etc.

The intrinsic hardware and software induced position uncertainties have been determined from measurements of the distance to a fixed mirror target, in this case a shutter in the DIII-D port. Shown in Fig. 5(b) is the measured shutter position as a function of time (i.e., multiple measurements) at a rf frequency of 41.2 GHz, approximately the rf frequency \( f_{\text{start}} \) corresponding to the plasma start position data shown in Fig. 5(a), using the same sweep time as used for Fig. 5(a) and typical frequency bandwidths for CDM in DIII-D.\(^{1}\) In this case, the measured standard deviation in the position is \( \sim 2 \) mm, improved from \( \sim 4 \) mm before the hardware improvements described above were implemented, and comparable to the uncertainty in the plasma start position data shown in Fig. 5(a). Further improvement in system signal-to-noise ratio would improve the measurement position accuracy in accordance with the well-known relationship\(^{1}\)

\[
\delta r = \frac{c}{2 \beta \sqrt{S}},
\]

where \( c \) is the speed of the light, \( S \) is the signal-to-noise ratio, and \( \beta \) is the effective bandwidth, which depends upon the shape of the microwave spectrum being used. It should be emphasized that the data analysis technique used to obtain the position data shown in Fig. 5(a) and typical frequency bandwidths for CDM in DIII-D.\(^{1}\) were determined using the radar ranging capability of the system, with CDM phase extraction, etc., while the plasma start position data shown in Fig. 5(a) were obtained using the signal amplitude analysis technique presented in the previous section, with no radar ranging or phase/time delay extraction. It should also be noted that reflectometer measurements of the plasma electron density profile do not have a constant positional accuracy; the accuracy varies with plasma conditions, in particular the local plasma gradient and plasma turbulence levels.

FIG. 5. Reflectometer profile measurements by X-mode Q-band system for simple-as-possible plasma (SAPP) stationary \( L \)-mode experiment. (a) The zero density plasma start position for shot 109 513, and (b) reference shutter position as a function of time for shot 109 498. All data shown were taken with 100 \( \mu \text{s} \) time resolution.
With regard to time resolution, examples of profile measurements with 10 μs full band frequency sweeps are discussed in detail in Ref. 16. Here, two examples of profile measurement using O-mode polarization are shown in Fig. 6. The reflectometer components of these profiles are a composite of data from both Q- and V-band subsystems, with Thomson scattering data being used to define the edge and SOL plasma below the lowest reflectometer probing frequency (1.4×10^{19} m^{-3}). These reflectometer measurements were used to validate Thomson scattering measurements of small changes in edge pedestal location and gradient in experiments with varying neutral density penetration depths.\textsuperscript{19}

The error bar on the reflectometer data in Fig. 6 represents the measured standard deviation over a set of measurements.

VI. SUMMARY

Recent improvements to hardware and data processing for the DIII-D profile reflectometer system have resulted in improved spatial and time resolution. Hardware modifications included decreasing the noise in the FM sweeping circuitry, optimization of launch and receive horn angles, and optimization of mixer operating conditions, resulting in increased signal-to-noise ratio and reduced spurious reflections. An improved automated method has been developed to determine the zero density plasma start position more precisely, and adaptive data processing is implemented to cope with time and spatially varying density gradients. The system can now achieve an uncertainty in the zero density plasma start position of ~2 mm (previously ~7 mm), a position uncertainty with a fixed mirror target of ~2 mm (previously ~4 mm), and a time resolution of 10 μs (previously ~100 μs), providing a powerful tool to investigate fast density profile evolution during L-H transitions, edge localized modes, and other MHD activities on DIII-D.

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