Application of dynamic calibration and control waveform optimization techniques in the fast sweeping reflectometer upgrade on the HL-2A tokamak

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Abstract: High temporal-spatial density profiles, measured by the frequency modulated continuous wave (FMCW) reflectometer, are crucial for the study of particle transport and confinement, especially for the transient events. However, the conventional calibration methods and control waveform of the voltage controlled oscillator (VCO) source constraint the increase of the sweeping frequency (time resolution) and the accuracy of the probed location of the FMCW. In this work, two methods of dynamic calibration of the VCO are proposed to reduce the measurement error due to the high sweep rate, and the results are found to be consistent with each other. In addition, the control waveform of VCOs are re-designed considering the VCO calibration results and dispersions of the waveguide and cables. Therefore, the sweep/dead time has been shortened to be 10 µs/50 ns from 25 µs/5 µs and the accuracy of the detection location has been improved significantly. The density profiles and density fluctuations during the tearing modes are presented which demonstrate the capability of the upgraded reflectometer.

Keywords: Nuclear instruments and methods for hot plasma diagnostics; Plasma diagnostics — interferometry; spectroscopy and imaging

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1 Introduction

High temporal-spatial electron density measurement is crucial for the study of particle transport and confinement of fusion plasmas [1, 2]. The frequency modulated continuous wave (FMCW) reflectometer has been routinely used to measure the electron density profiles in tokamaks [3], which is calculated from the phase shift between the launched microwave and reflected microwave by a plasma cut-off layer [4]. The effect of the density fluctuation on density profile measurements has been explained via the simulations with the zero-cross counting and digital complex demodulation analyses [5]. A key improvement of the existing FMCW reflectometer is to probe the plasma much faster than the typical period time of the density fluctuations [6]. However, series of issues have been found in the case of rapid sweeping. Firstly, the voltage controlled oscillator (VCO) source shows obvious nonlinear performance and a time delay compared with the output of the arbitrary waveform generator (AWG). This could induce some errors of the measured plasma positions [7]. Secondly, the beat frequency (or intermediate frequency, IF, the output signal of the system) covers a wide bandwidth, which is beyond the acquisition ability and adverse to the data processing. And thirdly, the dead time to wait for the elimination of Gibbs oscillation occupies too large proportion.

Aims on the rapid sweeping, we have made some improvements. Two methods of dynamic calibration of the VCO are introduced and the calibration results are shown in section 2. In section 3, the setup of the control waveform of the VCO based on the dynamic calibration results is presented. The application of the improved FMCW reflectometer in the electron density profile and fluctuation measurements is described in section 4. Section 5 presents the conclusion.

2 Dynamic calibration of the VCO

The main parameters of the FMCW reflectometer on the HL-2A tokamak are summarized as follows [8]. It covers three frequency ranges, i.e., Q, V and W band, and is operated in X-mode polarization. It was installed at the low field side of the torus through the two meters long
overmoded waveguides. The pyramidal horn antennas are installed inside the vacuum chamber, and followed by the notch filter to protect the system from electron cyclotron resonance heating. The output power of each system is approximately 10 dBm. The beat frequency is ideally 11 MHz with a 10 µs sweeping period and 1.6 m optical path difference. The acquisition sampling rate is 60 MSa/s (up to 120 MSa).

For the microwave reflectometer, the detected position of the cut-off layer is determined by the launched frequency of the reflectometer. Thus, the accuracy of the launched wave frequency decides the errors of the measured density profile. For the static case, the response of the frequency to the control voltage can be easily and precisely measured with a spectrum analyzer. However, in the case of rapid sweeping, the response of the VCO source will be delayed and distorted due to the built-in capacitive components [7]. Meanwhile, the spectrum analyzer cannot work in microseconds.

To overcome the limits caused by the fast sweeping, two ways of dynamic calibration of the VCO source are proposed. The setup of the two calibrations is illustrated in figure 1. In the subfigure (a), a sawtooth-like control voltage is applied to the VCO for a quasilinear sweeping. The microwave is mixed with a frequency tunable synthesizer and down converted to an IF signal, which is collected by the oscilloscope. The IF signal decreases to zero when the output frequency of the VCO equals to that of the synthesizer.

![Figure 1](image)

**Figure 1.** Two methods of the dynamic calibration of the VCO source: (a) mixed with a synthesizer, and (b) mixed with itself but with some time delay.

For the in & out phase (IQ) demodulator condition, an extremum of IF phase will be observed when the radio frequency (RF, launched wave for measurement) crosses the given local oscillator (LO, reference wave) frequency. By detecting that extremum, one frequency point can be calibrated. Figure 2 gives the example of the calibration when $f_{LO} = 11.6$ GHz using the first method (figure 1(a)). It is shown that at $t = 5 \mu s$ the IF equals zero ($d\phi/dt = 0$) in figure 2(c), which corresponds to 5.6 V of VCO voltage in figure 2(a). Among the graph, negative frequency occurs in case of IQ demodulation, and means that the $f_{RF}$ is lower than $f_{LO}$. Thus, one point of the $F$–$V$ relationship in the VCO calibration is obtained. For the calibration of all the other frequency points, just repeat the above procedure step by step by varying the LO frequency. Alternatively,
Figure 2. The example of the calibration when $f_{LO} = 11.6$ GHz using the first method, with (a) control waveform (left) and the calibrated frequency (right) of VCO, (b) time evolution of the IQ raw signals of the IF, and (c) phase (left, $\varphi = \arctan \frac{d}{Q}$) and frequency (right, $f_{IF} = d\varphi/dt$) of the IF.

A comb generator (instead of the synthesizer) can be used to generate multiple LO frequencies at one time [9].

Unfortunately, the computing error will increase with the IF frequency approaching zero [10].

In comparison, the second method in figure 1(b) is more operational and simpler. The sweeping microwave out of VCO is mixed with its own delay rather than the tunable synthesizer. That is to say, the beat frequency $f_{IF}$ is the down-conversion of the $f_{RF}(t)$ with $f_{RF}(t + \Delta t)$. Thus, the beat frequency $f_{IF}$ can be calculated as:

$$f_{IF} = f_{RF}(t + \Delta t) - f_{RF}(t) = \frac{df_{RF}}{dt} \cdot \Delta t = \frac{df_{RF}}{dt} \cdot \frac{l}{v}$$

(2.1)

where $f_{RF}$ is the launched frequency (to be calibrated), $l$ is the optical path difference, $\Delta t$ is flight time, and the RF group velocity $v$ approximates to light velocity $c$. Then, the phase of beat frequency $\varphi$ can be calculated via arctangent function for the case of IQ demodulation. Since the IQ frequency is far greater than zero, the error will be reduced. Thus, the launched frequency can be detected simply as:

$$F \approx \varphi \cdot \frac{c}{l} + C$$

(2.2)
where $C$ is a constant of indefinite integral, which can be determined in the process of calibration using the first method as shown in figure 2. In order to improve the accuracy, the delay path should be arranged in open space to avoid dispersion, otherwise the equation will become complex. And the dispersion during the path of coaxial cables and waveguides can be eliminated via twice measurements with the different delay path, i.e.,

$$\begin{align*}
\frac{d\varphi_1}{dt} &= \frac{df_{RF}}{dt} \cdot \left( \frac{l_{cab}}{v_{cab}} + \frac{l_{wg}}{v_{wg}} + \frac{l_{space}}{c} \right), \\
\frac{d\varphi_2}{dt} &= \frac{df_{RF}}{dt} \cdot \left( \frac{l_{cab}}{v_{cab}} + \frac{l_{wg}}{v_{wg}} + \frac{l_{space}}{c} \right),
\end{align*}$$

(2.3)

where $v_{cab}$ and $v_{wg}$ are group velocity of microwave inside the coaxial cables and waveguides separately. They are difficult to confirm, but can be avoided with a subtracting. It is noteworthy that more than one discontinuities surfaces will cause wave standing and oscillation of transmission coefficient [11], and therefore the optical lens and the waveguide probe without antenna should be reduced as possible. Hence the frequency out of VCO can be dynamically calibrated without dispersion interference:

$$\begin{align*}
f_{RF} &= (\varphi_1 - \varphi_2) \cdot \frac{c}{l_{space1} - l_{space2}} + C \quad (2.4)
\end{align*}$$

The comparisons of the VCO (model: XV0812, product of signal microwave) calibration between the two methods are shown in figure 3. Here, two methods give similar results, that the maximal $F - V$ difference (figure 3(c)) are less than 0.06 GHz (0.44%), and the maximal $\partial F/\partial t$ difference (figure 3(f)) are less than 0.5 GHz/µs for each sweeping rates. Compared to the static calibration, the maximal differences of dynamic calibration are 0.077 GHz (0.86%) at 10 kHz, 0.087 GHz (0.97%) at 100 kHz, and 0.381 GHz (4.22%) at 1 MHz respectively. In addition, the RF change rates are normalized to compare. For 10 kHz and 100 kHz sweeping, the results are quite consistent with eachother, but different from the 1 MHz case, that varies in $-0.5–2$ GHz/µs. However, for the 1 MHz sweeping, both the $F - V$ response and the frequency change rate $\partial F/\partial t$ show some deviations from others cases, and the difference $\partial F/\partial t$ is more significant at the beginning of the sweeping period, indicating that the measurement will become inaccurate without dynamic calibration for the 1 MHz or faster sweeping.

The IF frequency can be calculated according equation (2.1). Consider the measurement error with the following condition, sweeping rate of 1 MHz, path difference of 0.5 m, multiplier with 4th harmonic, RF dynamic error of 2 GHz/µs, the dynamic error of IF will estimated to be 13.3 MHz. It will cause about 20% phase error of the density profile at the edge area for the given case. Furthermore, the global gradient will be erroneously reduced without any correction, and the deformation is even worse. Accordingly, the dynamic calibration should be concerned, especially for the fast sweeping and higher harmonic multiplier.

### 3 Setup of the VCO control waveforms

The FMCW digitizer will collect the beat frequency directly, of which the bandwidth is expected to be narrower and stable to obtain a high quality signal that benefits the data processing. This can be achieved by delicately designing the VCO control waveform. As shown in equation (2.1),
Figure 3. The comparisons of the VCO calibration between the two methods, with (a) and (d) the $F - V$ response and $\partial F / \partial t$ with the first method (see figures 1(a), (b) and (e)) the $F - V$ response and $\partial F / \partial t$ with the second method (see figures 1(b), (c) and (f)) the difference of $F - V$ response and $\partial F / \partial t$ between the two methods. The black, blue, yellow and red curves stand for the VCO static case (without sweep), sweeping cases with the rate of 10 kHz, 100 kHz and 1 MHz, respectively.

we can design a control waveform for the VCO based on the dynamic calibration results (shown in the previous section) to obtain a desired sweeping microwave with frequency $F(t)$. And the beat frequency will be determined by $dF/dt$ directly. Nonlinear sweeping have been considered for the waveform design. Figure 4 shows the comparisons of four kinds of control waveforms, with (a) the traditional sawtooth-like wave, (b) first order continuous included, (c) upward and downward sweep, (d) dynamic calibration and dispersion of all the optical path concerned.

The time evolution of the VCO voltage is the inverse Fourier transform of its output frequency:

$$V(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} F(\omega) e^{i\omega t} d\omega$$

(3.1)

As the infinite high frequency is required during the inverse Fourier transform in equation (3.1), especially for the traditional sawtooth-like wave, the unexpected oscillations appeared at the beginning and ending of each sweep are shown in figure 4(a). The oscillation, the so called Gibbs phenomenon [12], acts on the RF microwave and has an adverse effect on the measurements. The Gibbs oscillation can be mitigated mathematically with the complex modification of the Fourier coefficient $F(\omega)$, but that is unfeasible to the arbitrary wave generator. Another way is to get rid
Figure 4. Modifications of the control waveform considering (a) nothing, (b) first order continuous, (c) forward and backward sweep, (d) dynamic calibration and dispersion of all the optical path.

The upward sweeping, from the low to high frequency, is commonly used. And the reverse sweeping with a mirror flip during the data processing is also effective. Figure 4(c) shows the alternate sweepings, and the dead time (between the adjacent sweeps) is 50 ns (supported by Agilent 33622A generator with the sinusoidal bandwidth of 120 MHz and the sampling rate of 1 GSa/s), which is much shorter than the existing reflectometers.

The velocity $v$ in equation (2.1) varies with the dispersion of all the optical path, including waveguides and coaxial cables. In addition, the optical difference $l$ is various for different distribution of the cutoff layers. Here, a typical density profile is used for the $l$ calculation. Thus, the $dF/dt$ can be computed for a constant $f$, and the sweeping frequency $F(t)$ is obtained with an integral. The waveform $V(t)$ via the dynamic calibration described in previous section is shown in figure 4(d) with the dispersion of all the optical path concerned.
With the improvement in the VCO control waveform mentioned above, the performance of the FMCW reflectometer was evaluated during the HL-2A plasma discharges. Figure 5 shows the results of HL-2A shot 32390. The IF signal is well recovered shown in subfigure (a), and the better SNR ensured the processing of phase. The quasilinear evolution of phase shown in subfigure (b) is designed for a simpler way to fix the unexpected jump shift. In (c) and (d), the upward sweep and downward sweep cases show quite consistent results in raw phase and density profiles. Accordingly, the alternate sweeping is functional and the dead time is reduced effectively, which is beneficial to the data processing and the temporal-spatial resolution is improved.

![Figure 5.](image)

Figure 5. (a) The time evolutions of IQ raw signals (left) and the VCO control waveform (right), (b) the time evolutions of phase calculated from IQ signals, and comparison of (c) phase with the RF frequency during the VCO upward and downward sweep, (d) the radial density profiles during the VCO upward and downward sweep.

### 4 Density profile and fluctuation measurements

In the realistic plasma discharges, the electron density can be varied in a wide range. Therefore, the feasible design of the IF signal should be concerned under the limitation of the digitizer sampling rate. On HL-2A, the FMCW reflectometer is continuously swept at the rate of 100 kHz with the IF frequency of 6–12 MHz and sampling rate of 60 MHz. The measured location can cover the whole plasma operation. The density profile evolution during ELM cycle in milliseconds was reported [8], and now density profiles in microsecond time scale during the tearing mode are shown in figure 6. The high time resolution enables a clear visualization of the perturbation on
density profiles during tearing mode, synchronized with the temperature signal from the electron cyclotron emission (ECE) radiometer [13], which indicates the density and temperature profiles are modulated by the rotation of the island.

The FMCW reflectometer can be seen as the equivalent of many fixed-frequency reflectometer systems, and hence, it can provide a continuous radial measurement from the plasma edge to the core [14]. By performing a temporal analysis of the swept signals for each launched frequency, one can determine the frequency spectra of the radial density fluctuations that shown in figure 7(a). Figure 7(b) shows the comparisons of the radial profiles of the density perturbation (by FMCW reflectometer) and temperature perturbations (by ECE) due to the tearing mode frequency. The perturbation profiles can illustrate the spatial structure of the tearing mode island [15, 16]. The density and temperature perturbations have analogical trend across the island region. But, the spatial resolution of the density perturbations is much better than that of the temperature perturbations, which provides much finer island structure, such as the island inner/outer boundary and the X-/O-point. The perturbation is maximum at the island boundary and minimum at the X-/O-point because of the relative flat density/temperature profile inside the island. Hence, the gap with a low level fluctuation at $R = 185$ cm can be detected as the X- and O-point of the island. The inner and outer boundary of the island are clearly shown at $R = 182.8$ cm and $R = 186.6$ cm, respectively. The island width is about 3.1 cm. The local maximum of the fluctuation at $R = 197$ cm matches the location of the plasma separatrix from EFIT reconstruction.

In addition, the impact of the tearing mode on the turbulent density fluctuation was investigated in figure 7(c). The turbulence level was estimated by integrating the power of the density fluctuations in the range of 10–50 kHz to avoid the tearing mode frequency. The turbulence level is reduced inside the island and elevated at the island boundary, which is consistent with the previous observations measured by the Doppler backward scattering reflectometer [17–21] and electron cyclotron emission imaging diagnostics [16, 22].
Figure 7. Radial evolution of (a) $n_e$ fluctuation frequency spectrum, (b) integration of $n_e$ fluctuation, and (c) $n_e$ fluctuation obtained by FMCW and compared with $T_e$ fluctuation by ECE.

5 Conclusion

In summary, aims on the rapid sweep FMCW reflectometer, two methods of dynamic calibration of the VCO source of the FMCW reflectometer are proposed and verified to be consistent with each other at a high sweeping rate. Based on the dynamic calibration results and dispersions of the waveguide and cables, the VCO control waveform has been delicately redesigned to reduce the dead time significantly between each sweep period. The temporal resolution of the Q- and V-band FMCW reflectometer has been shortened from 50 & 25 $\mu$s to 10 $\mu$s, with the dead time shortened from 5 $\mu$s to 50 ns, and the accuracy of the detection location has been greatly improved. Considering that the time resolution of the fastest reflectometer [14] is 1 $\mu$s with the dead time of 0.25 $\mu$s, the proposed sweep design is meaningful in the cutting edge. The higher time resolution gives this diagnostic fluctuation analysis abilities, and indicate that it will become an important tool to study the fast transport event in fusion plasmas. The identification of the tearing island fine structure, and the impact of the tearing mode on density profile and turbulent density fluctuations are presented, which demonstrates the high performance of the upgraded FMCW reflectometer.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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