*29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. **26B**, P-4.127 (2002)*

Time-of-Flight Refractometry for Robust Line-Averaged Density and Plasma Vertical Position Measurements on the T-11M Tokamak

V. Petrov, A. Petrov, A. Romannikov
State Scientific Center of Russian Federation TRINITI, 142190 Troitsk, Moscow region, Russia

Introduction

There are many physical experiments in tokamaks, which require reliable and simple measurements of plasma density (current ramp investigation, regimes with pellet-injection, MHD-oscillations, regimes with a long pulse, etc.). Usual phase interferometers do not completely satisfy these requirements due to fringe "jumps". Therefore, development of robust methods for measuring plasma density is rather actual. Specially it is important when the mean density is used for feedback signal in fuel feeding systems or in control systems of plasma position.

In this work the method of pulse time-of-flight refractometry (TFR) of plasma [1] is suggested for measuring line-averaged plasma electron density. Actually, this is a pulse reflectometer operating in a "pass-through" mode, when the carrier frequency of a probing wave ω is much higher than the plasma frequency ω_p. In this case the propagation time of a microwave pulse measured in plasma is proportional to the line density along the probing chord and. In this way, the unique relation between the propagation time τ_{gr} and line density n·l [1, 2] is provided:

$$\tau_{gr}(x) = \frac{\partial\Phi(\omega,x)}{\partial\omega}\Big|_{\omega 0} = \frac{1}{c}\cdot\int_l \eta(\omega,x,z)dz + \frac{\omega}{c}\cdot\int_l \frac{\partial\eta}{\partial\omega}(\omega,x,z)dz \approx \frac{k\cdot\int_l n(x,z)dz}{f^2} \qquad (1)$$

The main problem in such measurements is low accuracy of delay time measurements at small propagation times. The precision of measurements can be increased if one probes plasma by a wave with rather low carrier frequency such, that the dependence of the delay time on the density profile is not revealed yet.

In Fig. 1b, delay time of microwave pulse in plasma versus the carrier frequency of probe wave is shown for different density profiles: N (r) = N0 (β) $(1\text{-}r/a)^{\beta}$, β = 0.3, 1, 3. The mean density <n> is equal to $0.4\cdot10^{14}$ cm^{-3}. The dependence of results on density profile becomes very weak already at frequencies ~ 180 GHz (when the requirement $\omega >> \omega_p(0)$ is not satisfied, which corresponds to nonlinear mode of operation). The delay time is less than 0.2 ns in this case. It is possible to obtain a better precision of measurements if we use probing waves with two frequencies, so that measurements at a lower frequency give the mean density in a low-density regime. In Fig. 1 , delay time is shown versus frequency for the regime with <n> = $0.67{\cdot}10^{13}$ cm^{-3}. In Fig. 1d, the calibration curve of TFR in this mode is shown at the carrier frequency of 60 GHz. The result does not depend on the density profile within the accuracy of ±5%.

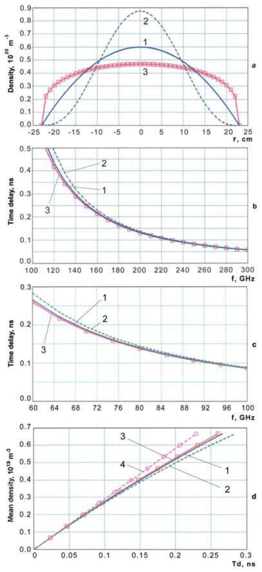

Fig. 1

One more way to improve the precision of measurements is to increase the pulse repetition rate (PRR) of probing pulses with the subsequent statistical averaging of *m* measurements. In this case, errors of measurements fall as $m^{-0.5}$, and the time resolution is proportional to *m* [1].

Experiments with TFR on the T-11M tokamak

In order to test the method in low-density regimes, a prototype of TFR at a carrier frequency of 60 GHz with output power ~100 mW was designed (see Fig. 2). To increase the sensitivity of TFR the probing in equatorial plane of tokamak was used, with a reflection of radiation from an internal wall of tokamak. For measuring the vertical displacement of plasma cord, two identical receive channels were placed symmetrically with respect to the transmitting antenna in one poloidal circumference (the 2-nd receive channel in Fig. 2 is not shown). In each receive channel the signals from two detectors (reference detector D1 and signal detector D2) were used. The forming of Start and Stop signals from the signals of detectors D1 and D2 is identical. In this way we minimized possible errors of the pulse locking times and improved the accuracy of delay-time measurements substantially (up to ~5 ps).

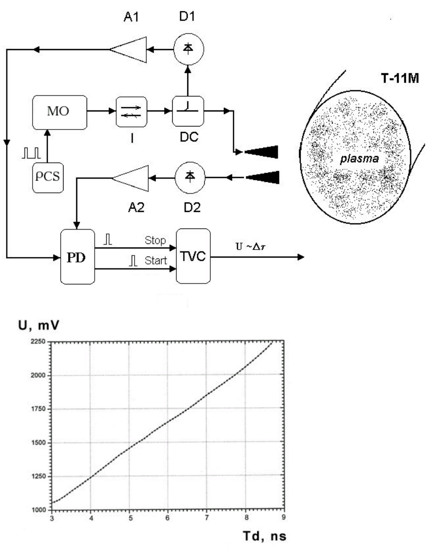

Fig. 2

The bench calibration of the instrument has been conducted before installation on the tokamak. Metal cylinder with a diameter of ~ 15 cm has been used as a reflecting target. The output signal from time-to-voltage converter (TVC) was measured by a digital voltmeter with the integration time of ~ 1 second. The calibration curve obtained is shown at the bottom of Fig. 2. The intrinsic resolution of instrument is about 5 ps at bench tests. Thus, minimal detectable displacement of the target is about 1 mm.

The sensitivity of dual TFR (DTFR) to vertical displacements of plasma column is determined by the relations:

$$z_h < \xi a^2/2h \text{ (for homogenous density profile),}$$
$$z_p < \xi a^2/6h \text{ (for parabolic density profile),} \qquad (2)$$

where ξ = 2 (U1-U2)/(U1+U2), is the minimal measurable signal difference in two channels in relative units (U1 and U2 are signals of 1-st and 2-nd channels of TFR, accordingly), 2h is a vertical distance between receiving antennas (2h = 6 cm for the T-11M).

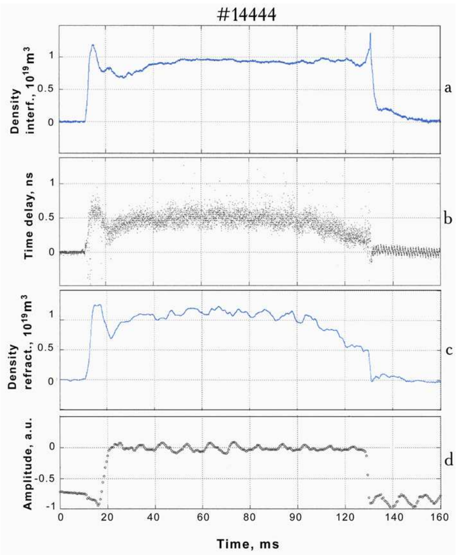

Fig. 3

In these experiments, we measured simultaneously the electron density using unambiguous polarization interferometer [3] with vertical probing. In Fig. 3, the TFR data, interferometer data, and signal of plasma vertical position from magnetic probes for discharge #14444 are shown. The intrinsic noise of refractometer signal without plasma corresponds to the minimal measurable density $n_{min} \sim 0.2\cdot10^{12}$ м$^{-3}$ at the time resolution of 2-3 ms. Therefore, the precision of density measurements with TFR is approximately 2 % at the maximum of density. From relation (2) we have $\xi \sim 0.02$ and $z_p <$ 0.4 cm for the mean density 10^{13} м$^{-3}$. Variations of the signal of TFR and plasma cord vertical position are well correlated.

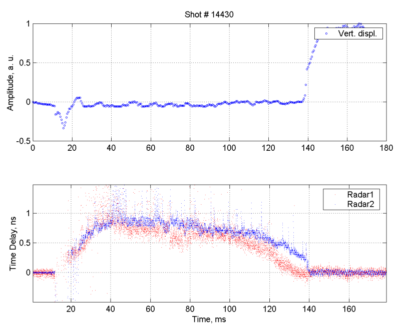

Fig. 4

In Fig. 4, signals of DTFR and the signal of plasma vertical displacement (magnetic probe) are shown for a shot #14430. At the stationary stage of discharge, a good vertical stability of plasma cord is observed, which follows from both the TFR data and the magnetic probes data. After 100-th ms, when current drops, an asymmetry of the DTFR signals is observed, which seems to be connected with a contraction of plasma cord and with the asymmetry of density profile at this stage. This assumption is confirmed by interferometer measurements.

The differential signal of DTFR, which is proportional to plasma cord vertical displacement if we assume symmetrical density profile, can be used as input signal for a plasma vertical position control system at the stationary stage of discharge.

Conclusions and future work

1. The method of pulse time-of-flight refractometry (TFR) of plasma has been experimentally tested on the -11 tokamak in low-density regimes. The method provides unique measurements of mean electron density in plasma. The method is rather attractive for large tokamaks, especially operating with a long pulse (Tore-Supra, ITER, etc.).

2. The accuracy of density measurements of ~ 2 % is obtained at the time resolution of ~ 2-3 ms. There are possibilities for further improvement of measurement precision by 3-10 times on the T-11M by increasing PRR of probing pulses from 100 kHz to 1-10 MHz.

3. A simplicity of access to plasma, uniqueness of measurements, and rather good sensitivity allow us to recommend DTFR to use in systems for maintenance of vertical equilibrium of plasma column.

4. Development of the technique:

- development and application of TFR for measuring density in the T-11M tokamak in the regime of nominal density (the carrier frequency ~ 140 GHz);
- development and manufacturing of plasma vertical position probe in the T-11M tokamak using DTFR;
- application of the technique for measuring a horizontal displacement of plasma column using probing plasma in vertical direction.

5. Adjustment of the technique for application on modern tokamaks (Globus-M, FTU) and ITER (probing with X-wave in the frequency range of ~ 100 GHz).

References

1. Shevchenko V. F., Petrov A. A., Petrov V. G., and Chaplygin Yu. A. Delay-Time Techniques for Probing a Tokamak Plasma with Microwave Signals. Plasma Physics Reports. Vol. 22, 1996, pp. 21-27.

2. S. H. Heijnen et al. Proc. 22nd EPS Conf. On Contr. Fusion and Plasma Phys. Bournemouth. 3rd-7th July 1995. P. IV-441.

3. Shevchenko V. F., Petrov A. A., Petrov V. G., and Chaplygin Yu. A. Polarization Microwave Interferometer with Unambiguous Phase Reading for Measurements in the T-11M Tokamak. Plasma Physics Report. Vol. 22. No. 1, 1996, pp. 32-37.