Microwave reflectometry for density profile and turbulence measurements on the COMPASS tokamak

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Introduction

Microwave reflectometry is an established radar technique to acquire various scientific results in plasma fusion research. Fast electron density profile measurements are crucial for the study of fusion plasmas and the operation of fusion devices. Operation capability and first results of the reflectometry on the COMPASS tokamak are presented in this contribution.

Device and diagnostic description

The microwave reflectometry system on the COMPASS tokamak consists of the three O-mode bands: K (18-26.5 GHz), Ka (26.5-40 GHz) and half of U (40-54 GHz) in the heterodyne detection scheme [1]. The transmitting and receiving quasi-optical band-combiners and the antennas are installed outside the low-field side midplane port. The voltage-controlled oscillator (VCO) runs either in the fast sweeping regime or as the synthesizer in the frequency hopping mode. In this way the measurement of density profiles can be alternated by the fixed frequency for the plasma turbulence and filament studies. The VCOs 8-13.5 GHz are followed by the frequency multipliers Fx2 in the K-band, Fx3 in the Ka-band and Fx4 in the U-band (Fig. 1). The system has the capability to measure the electron density profiles in the density range 4×10^{18} -3.6×10^{19} m^{-3}. The intermediete frequency IF as well as I/Q signals are recorded at 200 $MSamples/s$ for the post-processing. In the typical operational scenario the frequency sweeping consist of a 6μs long sweep part and a 1.5μs break. Usually we use 4

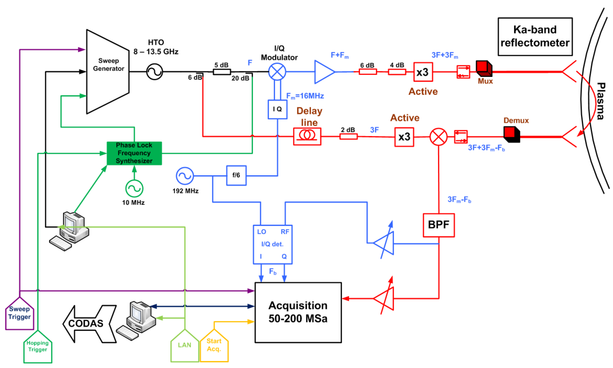

Figure 1: *Scheme of the Ka band reflectometer*

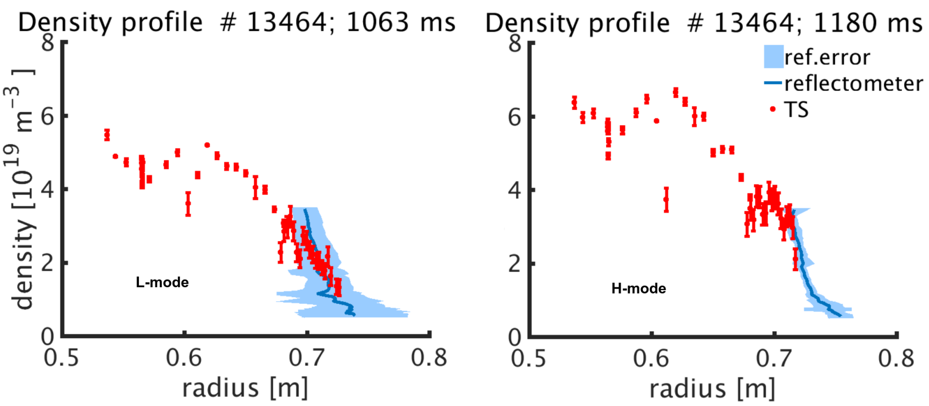

Figure 2: *Comparision of the reflectometer reconstructed profile with the Thomson scattering profile during the L-mode and H-mode, #14364*

sweeps to calculate one averaged profile. In this way we measured density profiles with the time resolution up to 30 μs so far [2].

Density profile signal processing

The electron density profile is obtained from the phase shift of the probing wave that is reflected by a plasma cut-off layer. O-mode wave with the frequency f propagates towards the plasma cut off-layer . There the refraction index N becomes zero and the wave is reflected. Temporal variation of the phase φ of the reflected wave is due to changes of the swept frequency and the optical path between the antenna and the cut-off layer. Then the group delay time is defined in the terms of range of sweeping frequency $F_{\rm P}$ and sweep time ΔT. The beating frequency $f_{\rm b}$ is evaluated by the spectrogram technique [5]. The radial position of cut-off layer can be analytically performed by the Abel inversion integral [3] $\tau_{\rm g} = \frac{1}{2\pi}\frac{\partial\varphi}{\partial f} = f_{\rm b}(t)\left(\frac{\Delta F_{\rm P}}{\Delta T}\right)^{-1}$. To obtain $r_{\rm c}(f_{\rm c}) = \frac{c}{\pi}\int_0^{f_{\rm c}} \frac{\tau_{\rm g}(f)}{\sqrt{f_{\rm c}^2 - f^2}}\,df$, the Mazzucato algorithm [4] was used.The advantage of this algorithm for O-mode reflectometry is that the calculation of each profile is reduced to a simple matrix multiplication.

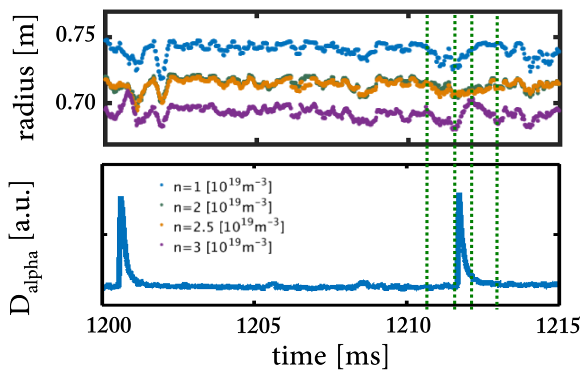

Figure 3: *Evolution of reflectometer density during ELM, #14362*

Experimental results

Fig. 2 shows comparisons of the reconstructed density reflectometer profiles with measured profile from the Thomson scattering system (TS). Higher turbulence levels in the low density part cause the dispersion of reconstructed profile. The error bar around the average profile is calculated from 5 profiles. In H-mode during the inter ELM phase the error bars are narrower.

In both plasma regimes the TS and reflectometry profiles align well to each other.

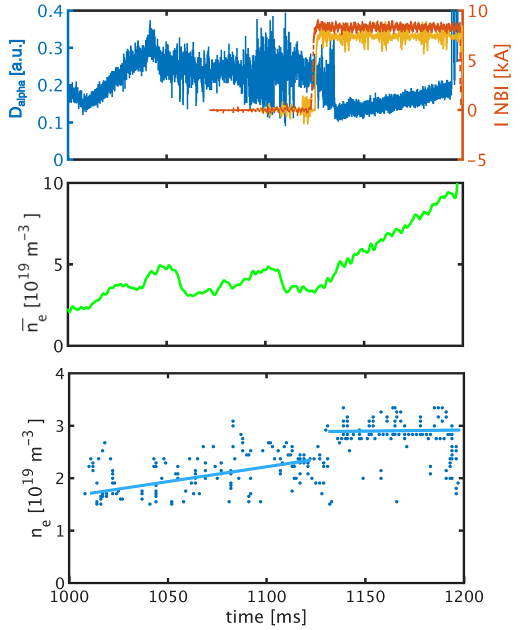

Figure 4: *Separatrix density at the transition from L-mode to ELM-free H-mode by NBI heating, #14370*

A radial separation of approximately 1-2 cm can be caused by the mapping of vertical TS to the mid-plane. This discrepancy depends on the plasma position and elongation. The time evolution of density profile is shown in Fig. 3. Upper part shows the evolution of the position for four densities representing the whole range. Each point is taken from one profile calculated from 4 sweeps and the time between profiles is 30 μs. On the radial movement of plasma density we observe the crash of the pedestal density by ELMs and the recovering of the gradient. In the precursor phase all densities move in correlation but the pedestal crash affects mostly the highest density in comparison to the other. For SOL physics the density at separatrix is important parameter. Although the density in the separatrix region (from EFIT magnetic reconstruction) is strongly affected by turbulence, the L-H transition is clearly seen in the time evolution of the reflectometry data (Fig. 4).

In the H-mode the line average density increases, but the separatrix density stay constant at the value $\frac{n_{e,sep}}{n_G} = 0.12$. Density profile evolution during the ELM event can be described by three characteristic phases [6]. The precursor phase with oscillation at 250-300 kHz is beginning 150 μs before the ELM crash (Fig. 5). During the ELM collapse phase with strong MHD activity, low density oscillations increase and radial movement of the isoline density layer is observed.

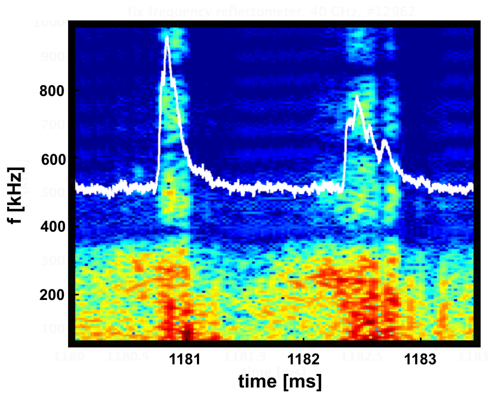

Figure 5: *Power spectrum from the 40 GHz ($n_e = 2 \times 10^{19}$ m^{-3}) reflectometer channel for # 12962*

Fixed frequency filament monitor

The heterodyne detection is utilized during the fixed frequency operation. The in-phase/quadrature detection allows to analyze phase $\phi(t)$ and amplitude $A(t)$ signals. The probing frequency determines the observed density and for its position other diagnostics like TS have to be used. We use the Seo algorithm [7] to get the phase and amplitude signals for the filament studies. A simple 1D geometrical model provides a analysis of the radial velocity of the cut-off layer from the derivative of the phase. $V_r = \frac{d(\Delta\phi)}{dt}\frac{c}{4\pi F_p}$. By a peak detection method of the V_r signal [8] we can detect the filament activity during the ELM cycle. A filament in front of antenna is represented by a positive and a negative peak on the V_r signal.

Response of reflectometer signal to the ELM event is in agreement with magnetic coil and divertor probes measurements. Filament activity during the ELM cycle with and without RMP (resonant magnetic perturbation) was studied on the Ka band with fix frequency at 40 *GHz*. An ELM synchronisation was applied on the reflectometry data. 0 *ms* is time of rising edge of the D_{alpha} signal. Fig. 6 shows the histogram of the propability density function of the peak detection time. H-mode and ELMs were affected by the RMP. Filament activity is distributed to the longer time with RMP that induce that the propability of filament present during the maximum activity is lower.

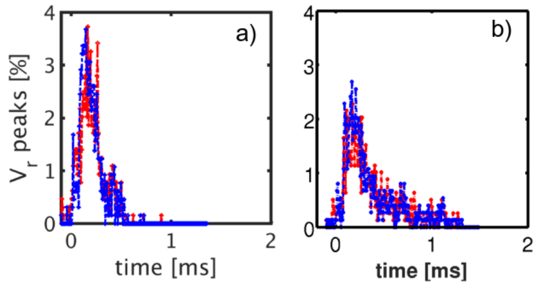

Figure 6: *Filament activity along the ELM cycle measured by 40 GHz reflectometry: PDFs of times of detection of positive (red) and negative peaks (blue) without RMP (a) and with RMP (b)*

Summary

The reflectometry system on the COMPASS tokamak provides the posibility to characterise the dynamic behavior of the plasma density profile with a high temporal resolution and good spacial resolution. From shot to shot we can change the operation mode from density profile mode to the fixed frequency mode. The density profile is consistent with the TS density profile. The fast sweeping allows us to track individual ELM phases and in the fixed frequency operation we observe the turbulance structure in the density and the filaments population during ELMs.

Acknowledgements

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