Synthetic radial correlation Doppler reflectometry diagnostic for FT-2 tokamak.

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Introduction

Turbulent transport plays a key role in plasma confinement which makes understanding and control of plasma turbulence one of the major goals of fusion research. The tools for turbulence characterization include radial correlation reflectometry, which probes the coherency between two cutoff layers using two microwaves at different frequencies incident normally onto magnetic surface. By performing correlation analysis of reflected signals, the information about turbulence properties, such as radial correlation length can be extracted. However, due to dominant contribution of small-angle scattering off long-scale fluctuations in the reflected signal, the radial correlation length is overestimated at small turbulence levels [1, 2]. One of the methods to counteract this effect is so-called radial correlation Doppler reflectometry (RCDR) or backscattering (BS) technique, which utilizes probing beam at oblique enough incidence to suppress small-angle scattering contribution to the BS signal. This approach was justified in analytical theory [3] and applied in FT-2 tokamak experiment, where the first comparison of the RCDR data to the results of the global gyrokinetic (GK) modeling with ELMFIRE code was performed [4].

In the present paper benchmarking of drift-wave turbulence characteristics provided by the GK code against the experimental data is performed using synthetic RCDR diagnostic based both on reciprocity theorem valid in linear theory and on full-wave IPF-FD3D code [5]. The latter code is accounting for the nonlinear effects, in particular, for the multiple small-angle scattering leading to underestimation of the turbulence radial correlation length [6]. The importance of nonlinear effects for interpretation of the RCDR data was demonstrated.

Setup

The parameters of FT-2 discharge used for modelling are R=55 cm, a=8 cm, B_0 = 1.7 T, I_p = 19 kA, n_e^{max} = $4.2\cdot10^{13}$ cm^{-3}. This discharge was modelled by ELMFIRE GK code and the resulting density profile was used for synthetic RCDR diagnostic. The parameters of diagnostic coincide with experimental data: the X-mode probing was performed horizontally from high field side by antenna that could be vertically shifted from the tokamak midplane by up to 2 cm. The considered probing frequencies were in the range of 66-74GHz.

In the linear synthetic diagnostic the density profile obtained from ELMFIRE was divided into background (mean) profile and fluctuations by averaging of the electron density over time. The fluctuations $\tilde{n}(\vec{r},t)$ were used to calculate the Doppler reflectometry signal, according to the following formula, derived from the reciprocity theorem [7]:

$$A_{S\omega}(t) = \frac{\sqrt{P_0}}{4} \int_V \frac{\tilde{n}(\vec{r},t)}{n(\vec{r})} \left[\hat{\sigma}(\omega,\vec{r}) \vec{E}_a(\omega,\vec{r}) \right] \vec{E}_a^{\,+}(\omega,\vec{r}) d\vec{r} \tag{1}$$

Here, the probing electric field $\vec{E}_a(\omega,\vec{r})$ was calculated using the density profile $n(\vec{r})$ based on experiment and $\hat{\sigma}(\omega,\vec{r})$ stands for the RF plasma conductivity tensor.

In the full-wave synthetic diagnostic direct nonlinear calculation of reflectometry signal with IPF-FD3D code was performed with three different types of input data:

1. Raw density data from ELMFIRE code output.
2. Same density fluctuations that were used in the linear synthetic diagnostics combined with experimentally measured background density profile (without Shafranov shift).
3. Fluctuations from p.2., but with their amplitude decreased tenfold.

Modelling results

The cross-correlation function (CCF) of synthetic backscattering signals, obtained within linear approach appears to be much broader than the experimental one (fig. 1). This difference can be attributed to a transition of the FT-2 RCDR experiment to the nonlinear regime of scattering, which appeals to creation of a nonlinear synthetic diagnostics. Therefore full-wave computations with FD3D code were performed for both raw density profile provided by ELMFIRE and the same fluctuations that were used in the linear synthetic diagnostic. A better agreement between the experiment and the full-wave synthetic diagnostics (blue curves in fig.1) confirms importance of nonlinear effects for the RCDR diagnostic at FT-2 tokamak. To further validate this conclusion, the amplitude of density fluctuations was decreased by a factor of 10, which led to widening of correlation function (purple curve in fig.1b), as predicted by the linear theory.

(a) (b)

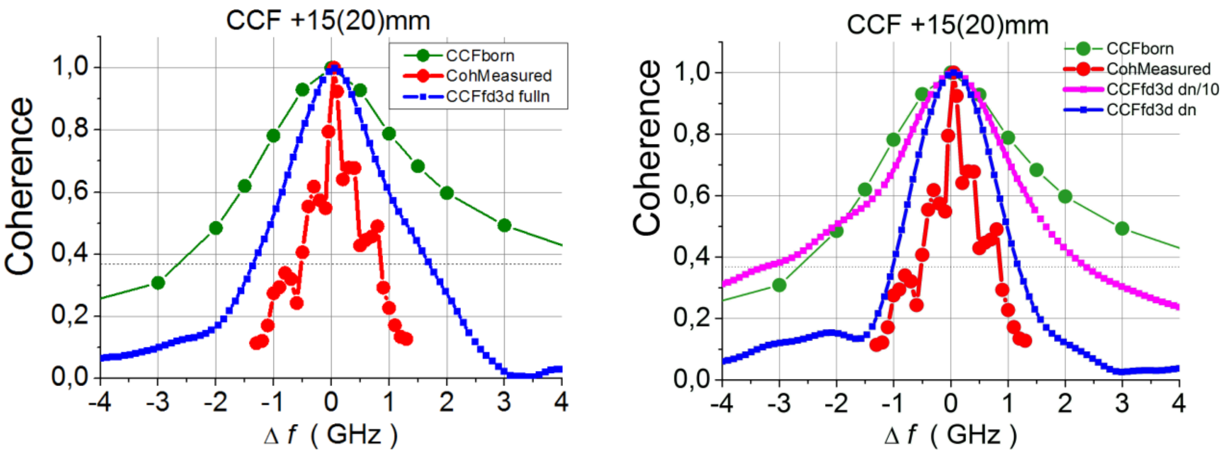


Fig.1. The RCDR CCF. Red curves - experimental measurements; green curves - linear synthetic RCDR; blue curves – full-wave synthetic RCDR with (a) raw ELMFIRE density distribution; (b) density fluctuations from ELMFIRE. The purple curve – case of density fluctuations decreased by a factor of 10.

The quadrature DR spectra were also calculated and compared with experimental data. Spectra obtained by linear technique turned out to be in a good agreement with experiment (green curves in fig. 2). However spectra provided by the full-wave technique demonstrated some differences. In particular, in the case of +20 mm antenna vertical displacement and raw density distribution given by the GK code the spectra appear to be shifted from the experimental one (see blue curve in fig. 2a).

(a) (b) (c)

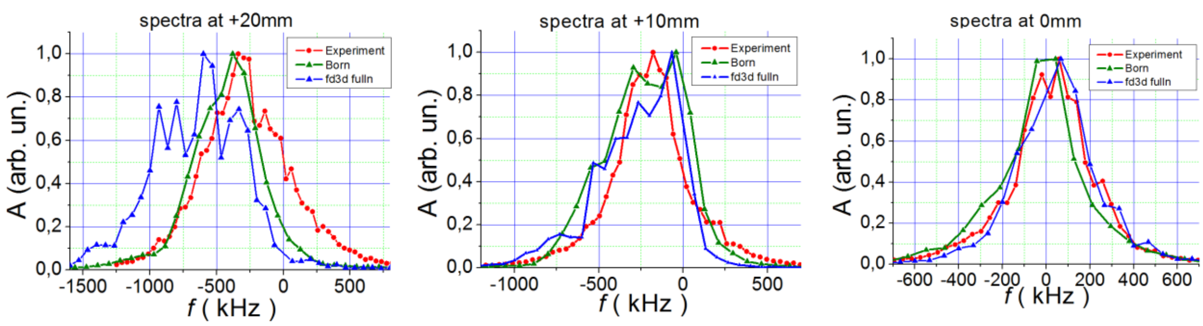
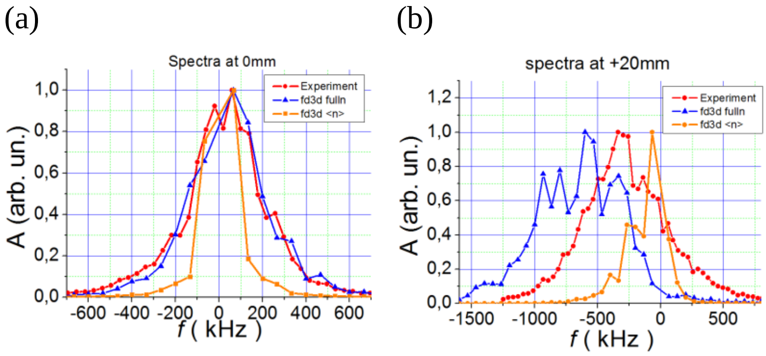


Fig. 2. Normalized DR quadrature spectra. Red curves - experimental measurements; green curves - linear modelling; blue curves - nonlinear modelling with raw ELMFIRE density. The antenna vertical shift is (a) +20 mm; (b) +10 mm; (c) 0 mm;

This shift is, at least partially, explained by the relaxation of the mean density profile provided by the GK code, which causes temporal variation of the synthetic DR signal phase. As it is seen in fig. 3, where the results of computation utilizing only the mean density distribution are shown, the relaxation provides a different spectral shift for different antenna positions, which is the largest for the maximal displacement – 20 mm (fig.3b). As an alternative method allowing to get rid of profile relaxation, a calculation utilizing the density fluctuations added to the stationary density profile was performed.



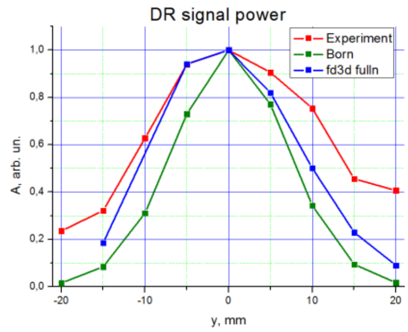


Fig. 3. DR quadrature spectra. Red curves - experimental measurements; blue curves – nonlinear modelling; orange curves – full-wave calculation with mean density. The antenna vertical shift is (a) 0 mm; (b) +20 mm

Fig. 4. Power of DR signal. Red curve - experimental measurements; green curve - linear modelling; blue curve - nonlinear modelling.

While the spectra computed in the case of density fluctuations indeed are not shifted, in the case of large antenna vertical displacement they include unexpectedly high frequency spectral components, which disappear when the amplitude of the fluctuations is decreased tenfold, therefore this case requires further analysis.

Another thing to note is that dependence of DR signal power on antenna displacement (fig. 4) was reproduced both in linear and nonlinear synthetic diagnostic. Since dependence corresponds to poloidal spectra of density fluctuations, this further validates GK modelling results. Experimental measurements show slower signal decay with growing displacement, which could be attributed to an underestimation of the level of small-scale turbulence component in the GK code.

Conclusions

Despite mentioned inconsistencies, synthetic RCDR diagnostic seems to successfully reproduce experimental results. This validates the results of ELMFIRE turbulence modelling and also confirms the suggestion of nonlinear scattering regime for X-mode DR in FT-2 tokamak. The paper results also demonstrate how significant the difference is between the linear and nonlinear regime, when it comes to radial correlation length evaluation.

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