Doppler Reflectometer System in the Stellarator TJ-II

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Abstract

A Doppler reflectometer system has recently been installed in the stellarator TJ-II. The system is optimized for the Q-band (33 – 50 GHz) and the high-curvature plasmas produced in TJ-II. The launch angle of the microwave beam can be controlled by a steerable mirror to obtain angles between $\pm 20°$ enabling the measurement of perpendicular wavenumbers in the range 3 to 15 cm^{-1}. The available angular range allows for comparisons between positive and negative values and additionally for calibration of the system. Localization and $k_\perp$–estimation is done via the 3D ray/beam-tracing code TRUBA. First measured spectra and radial profiles of the perpendicular velocity of plasma density fluctuations are presented.

The TJ-II Doppler Reflectometer System

In February 2009, a new Doppler Reflectometer System (DRS) was put into operation in the stellarator TJ-II. A detailed description of involved components (hardware and software) can be found in Ref. [1]. The electrical backbone [2] of the conventional reflectometer, in operation from 2004 to 2008, is used. In the design phase, central requirements for the system were the realization of a gaussian beam with plane phase fronts in the plasma and the possibility to change the angle of incidence of the beam on a shot-to-shot basis. The effect of the former is an optimization of the spectral resolution, while the latter allows measurements of the perpendicular wavenumber spectrum $S(k_\perp)$. The demands have been met by using an exclusively designed small choked-corrugated antenna and a steerable ellipsoidal focusing mirror. Additional strong constraints on the system were imposed by the complicated three-dimensional structure of the magnetic field of TJ-II. The diagnostic was inclined toroidally by an angle of 26°, which corresponds to the magnetic field pitch angle at the respective toroidal position. A schematic of the DRS in a plane perpendicular to the magnetic field is shown in Fig. 1 where the vessel walls are represented by thick solid

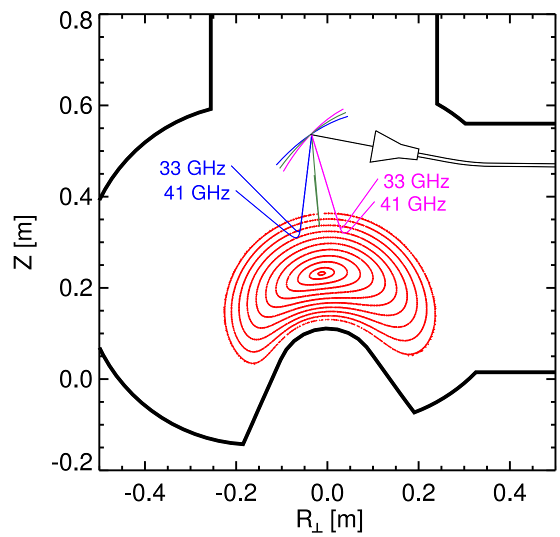

Figure 1: Sketch of the Doppler reflectometer system installed in TJ-II. Rays with launch angles $\theta_l = 0°$ (green) and $\pm 12°$ (+: magenta, –: blue) are shown.

lines. The flux surfaces are depicted for the standard configuration of TJ-II. The microwave beam emitted by the antenna is schematically represented and is reflected by the mirror to the plasma. If θ is the mirror angle with respect to the equatorial plane, $\theta_s = 42°$ is defined which is the mirror position for perpendicular incidence. Henceforth, the mirror inclination will be referred to as $\theta_l = 2(\theta - \theta_s)$, which is the launch angle with respect to perpendicular incidence. The factor “2” takes the law of reflection into account. In the figure, the mirror is plotted three times indicating different launch angles θ_l (-12°, 0°, 12°). The system was designed to be able to measure with positive and negative θ_l allowing for comparisons between $\pm\theta_l$ and a calibration of the system by searching for the value of θ_s, the angle of perpendicular incidence.

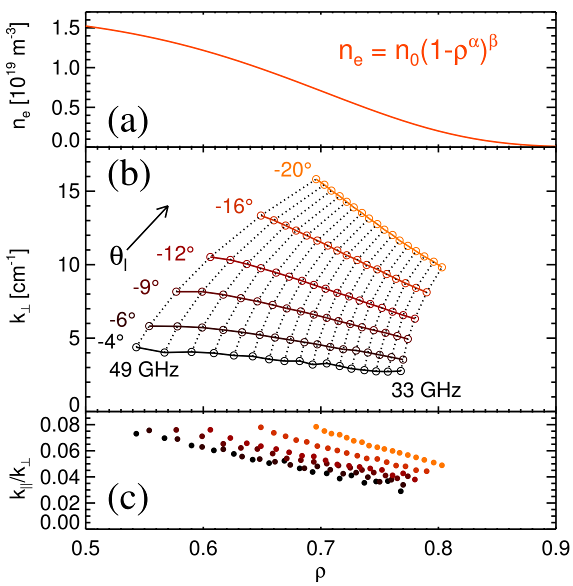

Figure 2: (b) Dependence of the perpendicular wavenumber $k_\perp$ on the radius ρ and different launch angles θ_l assuming the density profile shown in (a). (c) shows the fraction $k_\parallel/k_\perp$, which is always below 8%. For details refer to the text.

In Fig. 2(b) the dependence of the perpendicular wavenumber $k_\perp$ on the radius ρ and the launch angle θ_l is shown. The assumed density profile (a) is of the form $n = n_0(1-\rho^\alpha)^\beta$, where $n_0 = 1.7 \times 10^{19}$ m^{-3}, $\alpha = 6$ and $\beta = 7$, which is a reasonable fit to typical TJ-II profiles. In this case, a radial profile of $u_\perp$ can be measured for $\rho = 0.55 - 0.77$ while $k_\perp$ is almost constant. If the launch angle is changed and the microwave frequency is adapted adequately, the perpendicular wavenumber spectrum $S(k_\perp)$ can be obtained in the range $k_\perp = 3 - 15$ cm^{-1} at constant plasma radius (in this case $\rho \approx 0.7$). TRUBA also yields the parallel wavenumber $k_\parallel$, the fraction $k_\parallel/k_\perp$ is shown in Fig. 2(c). In the worst cases (high probing beam frequencies), $k_\parallel/k_\perp < 0.08$ holds, so the sensitivity of the DRS to parallel wavenumbers is negligible.

Experimental Results

First experimental measurements, recently obtained in both ECRH and NBI plasmas, show a Doppler shifted peak clearly separated from the 0$^{\text{th}}$ order symmetric component, which has a lower amplitude in most cases.

Fig. 3 shows typical spectra of the complex amplitude signal from the DRS for four different microwave frequencies at low density (① - ④: #20281, $\langle n_e \rangle \approx 0.5 \times 10^{19}$ m^{-3}) and one at higher density (⑤: #20277, $\langle n_e \rangle \approx 0.7 \times 10^{19}$ m^{-3}) discharges. Heating of the plasma was

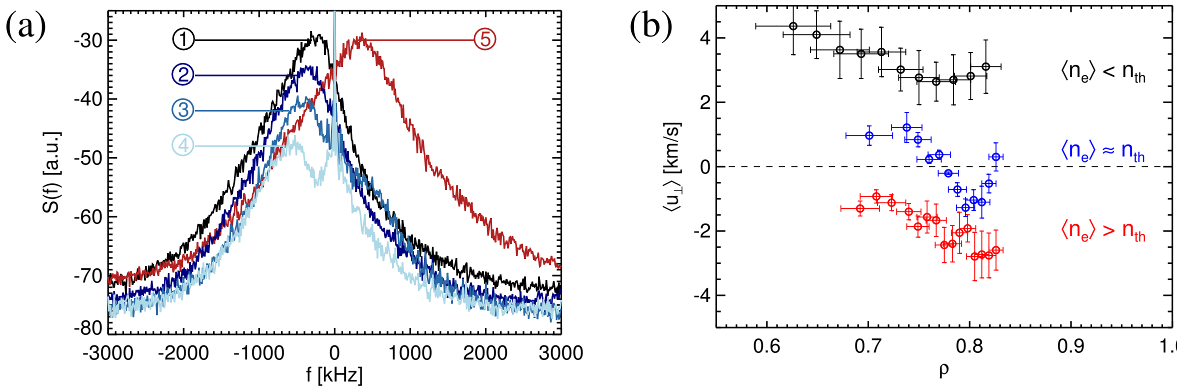

Figure 3: (a) Doppler shifted power spectra for four different microwave frequencies for a low-density ECRH plasma (① - ④, `#20281`) and for a higher density ECRH discharge (⑤, `#20277`). The launch angle is $\theta_l = -12°$ for all spectra. The Doppler peak is clearly separated from $f = 0$ kHz for both cases (low and higher density). (b) (`#20281, #20285, #20294`) Perpendicular velocity profiles in ECRH discharges with different line-densities.

done via ECRH with heating power $P_{\mathrm{ECRH}} = 500$ kW and the mirror angle was $\theta_l = -12°$. The Doppler shifted peaks ($m = -1$) are clearly visible in the negative frequency part for low densities and in the positive part for higher densities. To obtain the radial backscattering position and the perpendicular wavenumber, density profiles from the AM reflectometer [3] (with a radial uncertainty of $\Delta\rho = 0.01$, cf ref. [4]) are used as input for TRUBA. The Doppler shift f_D is calculated by fitting a Gaussian to the respective spectrum.

For the low-density plasma, the perpendicular velocity of density fluctuations increases towards the center of the plasma from 2.3 km/s at $\rho = 0.82$ (①) to 3.8 km/s at $\rho = 0.63$ (④). A reversal of the perpendicular velocity is observed in the high density example (⑤). In this case the perpendicular velocity is $u_\perp = -3.1$ km/s.

Fig. 3 (b) shows profiles of the perpendicular velocity of plasma density fluctuations for three discharges with different line-averaged densities. In the case where $\langle n_e \rangle < n_{\mathrm{th}}$ (n_{th} is a threshold density for the reversal of the perpendicular velocity), the perpendicular velocity is positive in the whole radial measurement range. For $\langle n_e \rangle > n_{\mathrm{th}}$, the velocity profile is reversed and the velocities are negative. These profiles confirm results obtained with Langmuir probes [5] and with the Heavy Ion Beam Probe [6]. For an intermediate case where $\langle n_e \rangle \approx n_{\mathrm{th}}$, the reversal of the perpendicular velocity is seen at an intermediate region $\rho \approx 0.8$. The inversion of the edge perpendicular plasma velocity as the density increases, already monitored with the conventional reflectometer [7] and shown to be connected to the radial position of maximum density gradient [4], is confirmed and the results are extended by the availability of absolute velocity values.

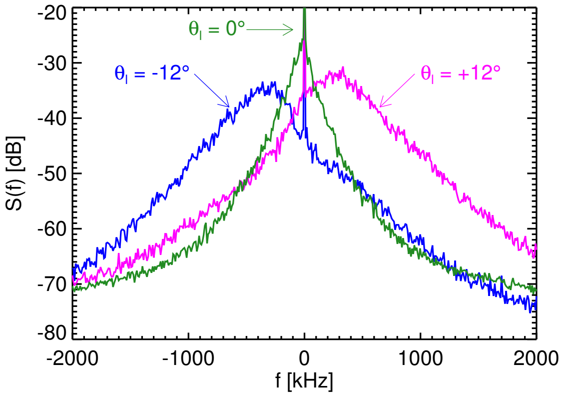

Figure 4: (#20281, #20297, #20361) Power spectra for different beam launch angles θ_l. The spectrum for $\theta_l = 0°$ is symmetric.

First measurements obtained in NBI plasmas show in general higher perpendicular velocities; further experiments are in progress to permit a detailed analysis [8].

In Fig. 4 power spectra of similar discharges but with different launch angles θ_l are shown. The spectrum for $\theta_l = 0°$ is symmetric, while the other two spectra ($\theta_l = \pm 12°$) are Doppler shifted with similar absolute values of the Doppler shift, but different sign. The value obtained experimentally for θ_s is 41.9°, which coincides well with the theoretical value ($\theta_{s,th} = 41.6°$).

Summary

The antenna system of the conventional reflectometer of TJ-II has been replaced recently by a newly developed combination of choked-corrugated antenna and steerable ellipsoidal mirror. The new system permits Doppler backscattering measurements in X-mode with a frequency range of 33 – 50 GHz with positive and negative launch angles θ_l. Accessible values for the perpendicular wavenumber are 3 – 15 cm^{-1}, and the influence of $k_{||}$ has been shown to be small. In addition, the system can be operated in a conventional (perpendicular incidence) reflectometry configuration. Profiles of the perpendicular velocity of density fluctuations confirm and deepen results previously obtained in TJ-II. The successful and reliable operation has been demonstrated and the system is now being used as a standard diagnostic in the operation of TJ-II.

References

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