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Doppler Reflectometry : Measuring the Propagation Velocity of Density Perturbations

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Abstract

Doppler reflectometry is a radar measurement where a microwave signal probes the plasma with a line of sight which is non-perpendicular with respect to the reflecting layer. According to the Bragg condition the diagnostic selects density perturbations with finite wavevector $K_\perp$ in the reflecting layer. From the Doppler shift of the returning microwave signal the propagation velocity $v_\perp$ perpendicular to the magnetic field can be obtained whereas the signal intensity contains information about the perturbation amplitude. The diagnostic capability of Doppler reflectomery is discussed and results from the W7-AS stellarator are presented. During stationary phases the measured values $v_\perp(r)$ and their radial dependence are in good agreement with the $\boldsymbol{E} \times \boldsymbol{B}$ velocity of the plasma obtained from passive spectroscopy. Transient states of the plasma can be followed with a temporal resolution of less than 50 μs. Therefore Doppler reflectometry allows one to measure the interdependence of sheared flow and turbulence on that timescale.

Keywords:

reflectometry, plasma rotation, shear flow, turbulence, $\boldsymbol{E} \times \boldsymbol{B}$ velocity, ELM

1. Introduction

A mechanism which is believed to cause phase transitions and bifurcations in a plasma is the interdependence between the wavenumber spectrum of perturbations $K_\perp$ and the shear of their propagation velocity perpendicular to the magnetic field $v_\perp$. However, diagnostic access to the relevant quantities is hard to obtain: most fluctuation diagnostics applicable to the confinement region of the plasma lack sufficient resolution either in space (like microwave scattering) or in time (like diagnostics applying correlation techniques such as beam emission spectroscopy and correlation ECE). Besides, the temporal resolution of spectroscopic methods, which measure the $\boldsymbol{E} \times \boldsymbol{B}$ velocity $v_{E\times B}$ of the underlying background plasma is not better than 1 ms. In this paper we introduce Doppler reflectometry as a tool for the localized measurement of $v_\perp(r)$ with a temporal resolution of less than 50 μs. Doppler reflectometry [1-4] probes the plasma by a microwave signal with a line of sight which is non-perpendicular with respect to the reflecting layer. Density perturbations with finite wave number $K_\perp$ in the reflecting layer result in higher diffraction orders for the returning microwave which are selected by the tilt angle of the antenna θ_{tilt}. Thus the antenna corresponds to a bandpass filter in $K_\perp$-space of the perturbations where $K_\perp$ can be varied by a scan of θ_{tilt} and where the bandwidth $\Delta K_\perp$ depends on the antenna pattern. This is in contrast to conventional reflectometry dedicated to measure the stratified background density profile which uses a line of sight perpendicular to the reflecting layer

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such that the antenna acts as a low-pass filter receiving the 0[th] order of reflection. For typical conditions in microwave reflectometry the K-selectivity of the antenna is insufficient to suppress the respective unwanted order completely. Additional filtering in the frequency spectrum becomes possible if the spectral features can be separated by a sufficient Doppler shift of the diffraction orders. Vice versa this Doppler shift displays the propagation velocity $v_\perp$. Simultaneously, the microwave power received in the respective -1[st] diffraction order is a fast monitor for the turbulence level. Such Doppler reflectometry provides direct access to the interdependent properties of the propagation velocity $v_\perp$ and the $K_\perp$-spectrum of density turbulence.

2. Principles and Constraints of Doppler Reflectometry

The principle of Doppler reflectometry is explained in Fig. 1 using the model of a moving reflection grating in vacuum with small sinusoidal corrugation characterized by a wave number $K_\perp = 2\pi/\Lambda_\perp$. For the -1[st] order of the diffraction pattern to return to the antenna the Bragg condition requires

$$K_\perp = 2 \cdot k_0 \cdot \sin(\theta_{\text{tilt}}) \qquad (1)$$

where k_0 is the wavevector of the microwave. By a variation of θ_{tilt} the $K_\perp$-spectrum of the density perturbations can be scanned. If the reflection grating propagates with a velocity $v_\perp$ the returning microwave is modulated by the periodic structure and the frequency of the wave diffracted in -1[st] order is Doppler shifted by

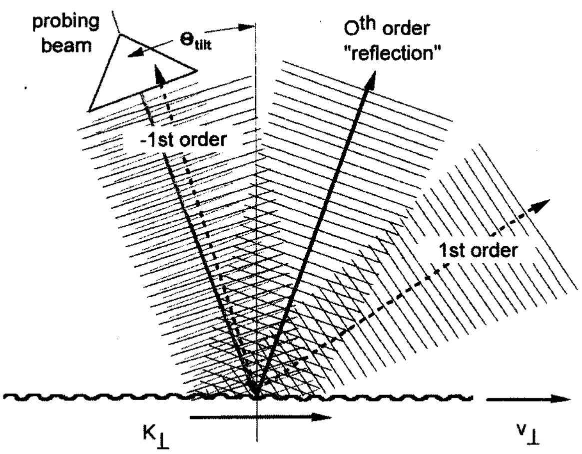

Fig. 1 Principle of Doppler reflectometry illustrated by a reflection grating in vacuum and a single antenna arrangement.

$$\Delta\omega = -\vec{v} \cdot \vec{K} \qquad (2)$$

For density fluctuations in magnetically confined plasmas it is usually assumed that $\boldsymbol{K} \perp \boldsymbol{B}$. It then follows from the scalar product in eq. 2 that the Doppler shift only results from the velocity component of the perturbations *perpendicular to the magnetic field* (i.e. in the direction of $v_{E \times B}$) independent of the (toroidal and/ or poloidal) orientation of the antenna tilt θ_{tilt}!

It is important to point out the crucial role of an optimised antenna plasma geometry for the feasibility of the diagnostic: (1) Any error in the knowledge of θ_{tilt} directly enters the calculation of $v_\perp$ since $v_\perp \propto K_\perp \propto \theta_{\text{tilt}}$. "To get rid of changes in θ_{tilt} which may result from discharge conditions a differential measurement can be performed with two Doppler reflectometry systems and two antennas viewing the same spot with tilt $\pm\theta_{\text{tilt}}$." (2) In addition the selected wavenumbers K_{ant} depend on the orientation of the antenna tilt with respect to the grating. Changes in the direction of the magnetic field (i.e. of the local pitch angle) may result in a tilt direction which is not oriented perpendicular to the fieldlines. However, these effects are small since $v_\perp \propto K_\perp = K_{\text{ant}} \cdot \cos(\alpha) \approx K_{\text{ant}}$ where α is the angle between antenna tilt direction and magnetic field orientation. (3) The bandwidth ΔK of the antenna filter is ideally determined by the width of the antenna pattern alone. However, in realistic cases ΔK is increased by both non-ideal beams - i.e. non-parallel wavefronts - and/or by a finite curvature of the reflecting layer within the beam spot. In W7-AS the optimum spot diameter turned out to be limited in size by the poloidal curvature of the reflecting layer originating from the rather small minor radius. For the experiments Gaussian beams $E \propto \exp(-x^2/w_0^2)$ are used with the beam waist w_0 close to the reflecting layer which minimizes the effects of beam divergence. In addition Gaussian characteristics ideally have no side-lobes, which is of importance if the $K_\perp$-spectrum of the density fluctuations has pronounced maxima outside the selected spectral range. Such a maximum could significantly contribute to the received signal if it falls into a side lobe of the antenna.

The diagnostic potential of Doppler reflectometry depends on how accurately the local quantities $v_\perp(r)$ and $K_\perp(r)$ can be derived in a realistic plasma, i.e. in the presence of (1) a background density profile with finite gradient and (2) in the presence of density perturbations along the signal path. (1) : Analytical and numerical analysis [5] show that refractive effects due to the background profiles in the plasma do not perturb the measurement significantly and the probed wave vectors $K_\perp(r)$ and thus the $v_\perp(r)$ can be obtained directly from the geometrical antenna tilt and the wavelength in vacuum. In analogy to conventional reflectometry the swelling of the electric field close to cutoff results in an enhanced sensitivity to density perturbations in a narrow layer close to the nominal cutoff position. This layer is shifted radially outward if a finite θ_{tilt} is used. An analytic solution for this radial shift is given by Ginzburg [6]: the effective cutoff layer shifts to a position where the index of refraction becomes $\mu = \sin(\theta_{\text{tilt}})$. As a consequence the radial shift is reduced and the measurement is generally more localized if x-mode polarization is used instead of o-mode. (2): strong density perturbations resulting in multiple scattering and scattering into higher diffraction orders can disturb the localization of the measurement both in real space and in K-space. In particular an estimate of the turbulence level, i.e. the absolute power of the density perturbations $K_\perp(r)$ from a measurement of the absolute microwave power received in the -1st diffraction order, is possible only with a priori assumptions about the turbulence properties. However, the received microwave power can be used as a fast but uncalibrated monitor for the turbulence level.

3. Doppler Reflectometry Experiments at W7-AS :

Doppler reflectometry spectra obtained at the W7-AS stellarator (R = 2.0 m, average minor radius a = 0.17 m) with a heterodyne reflectometer are shown in Fig. 2. The experimental setup and the geometry of the antenna system are described in [4]. If the Doppler shift is sufficiently high (continuous line) the ± 1st diffraction orders can be well separated from the 0th order of reflection. The antenna arrangement is oriented such that the red-shifted feature indicates a poloidal propagation of the turbulence in electron diamagnetic direction. Due to the tight focussing of this antenna (w_0 = 1.9 cm ≈ $5\cdot\lambda_0$) the $K_\perp$-resolution is poor and also the +1st diffraction order enters the receiver as can be seen by the weak blue shifted spectral feature with same frequency shift $|\Delta f|$.

With increasing θ_{tilt} the peak of the spectrum shifts towards higher frequencies indicating that the antenna selects $K_\perp$ from a wave number spectrum which is considerably broader than the system resolution. A scan of θ_{tilt} can be performed on a shot to shot basis and examples for three timepoints of a discharge are given in Fig. 3. The range of wavevectors that can be selected

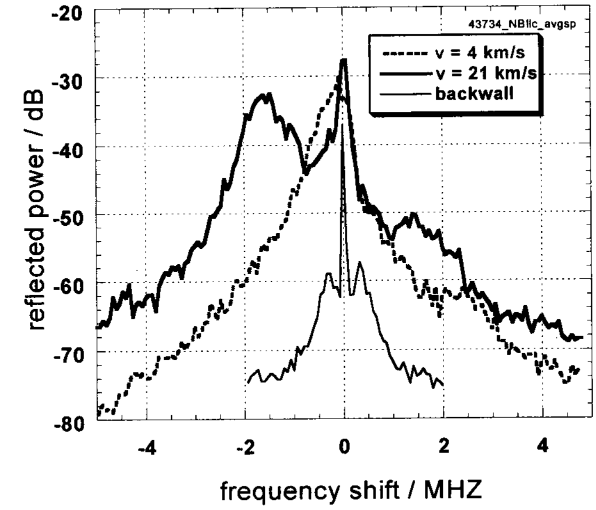

Fig. 2 Two examples of Doppler reflectometry spectra obtained with the heterodyne reflectometer and an antenna tilt of θ_{tilt} = 3°. For both spectra the probed position is reff = 14.2 cm, 3 cm within the plasma boundary defined by a limiter. The spectrum resulting from reflection at the torus backwall is given for comparison. Note the logarithmic scale of the vertical axis.

by $1° < \theta_{\text{tilt}} < 15°$ is $3.5\ \text{cm}^{-1} < K_\perp < 9\ \text{cm}^{-1}$. The lower boundary results from the finite width and Doppler shift of the -1st order of diffraction which overlaps with the 0th order of reflection for $\theta_{\text{tilt}} \leq 6°$ for this antenna system and experimental conditions. The frequency shift in Fig. 3 varies almost linearly with $\theta_{\text{tilt}} \approx \sin\theta_{\text{tilt}}$ indicating that the perturbations selected by the antenna propagate with a common constant Doppler velocity $v_{\text{Doppler}} = 2\pi\Delta f/\Delta K$.

The flux surface averaged velocity perpendicular to the magnetic field $v_\perp$ is calculated from the measured Doppler velocity v_{Doppler} taking into account the flux compression of the magnetic surfaces. At the chosen position in the W7-AS stellarator v_{Doppler} is increased with respect to $v_\perp$ by about factor of 2 to 3.5 depending on the magnetic configuration and the Shafranov shift. An example for the radial profile of the propagation velocities $v_\perp(r)$ is plotted in Fig. 4 together with $v_{E\times B}(r)$ as derived from active charge exchange recombination spectroscopy using He as a tracer impurity [7]. The measured propagation velocity of the density perturbations is the sum of two components $v_\perp = v_{E\times B} + v_{\text{turb}}$ where v_{turb} is the intrinsic phase velocity of the turbulence riding on the background plasma which rotates with $v_{E\times B}$. Under steady state conditions and for the ECRH discharges investigated so far the radial

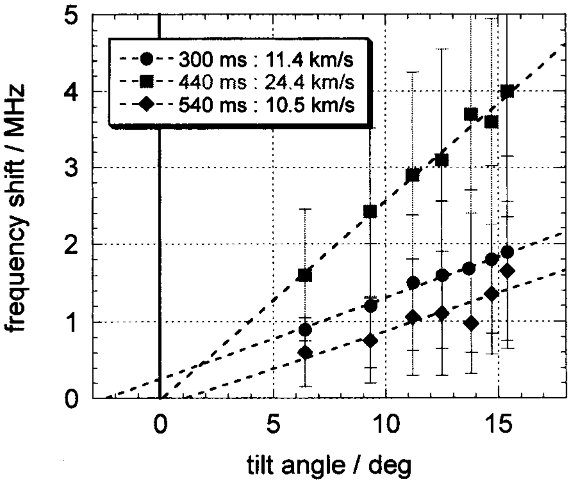

Fig. 3 Frequency shift of the -1st diffraction order as a function of θ_{tilt} for three different times of a discharge with changes in the confinement properties. The probed density (x-mode, f = 85 GHz, B_{tor} = 2.5 T) is always ≈ $2{\cdot}10^{19}$ m^{-3}, the radial position of the nominal cutoff-layer is 2–3 cm inside the limiter position. Vertical bars indicate the –10dB width of the Doppler shifted feature (for comparison see Fig. 2). The resulting Doppler velocities $v_{Doppler}$ are also included.

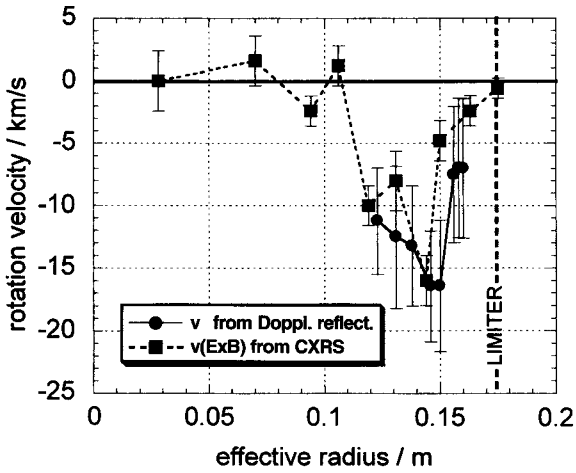

Fig. 4 Radial profile $v_\perp(r)$ compared with the profile $v_{E\times B}(r)$ as obtained from active Charge Exchange Recombination Spectroscopy (CXRS). Vertical bars indicate the –10dB width of the Doppler shifted feature. As an example an ECRH heated discharge is shown.

profile $v_\perp(r)$ is always identical within the error bars to the profile of $v_{E\times B}(r)$ evaluated from spectroscopy. Therefrom we conclude that for these conditions the contribution of the intrinsic phase velocity of the turbulence v_{turb} must have been small.

An example for the capability of the Doppler reflectometer to follow dynamic phenomena is given in Figs. 5, 6 which show Doppler reflectometry measurements obtained with heterodyne detection during a strong Edge Localized Mode (ELM)-like event [8]. The probed layer is located about 2 cm inside the separatrix. The fast evolution of the signal is measured by 6 Bandpass filters (Δf = 250 kHz) with a temporal resolution of ($\tau \geq 20$ μs). Their center frequencies are chosen to measure the red-shifted (corresponding to electron diamagnetic direction) radiation of the heterodyne reflectometer at six values in the frequency interval –2.5 MHz < $f_{Doppler}$ < –0.5 MHz. Examples of spectra measured at four time slices are given in Fig. 5. In Fig. 6a the temporal evolution of the Doppler reflectometry spectra is shown as a grey scale plot. The total power received in -1st diffraction order and the Doppler shift of the spectral feature are obtained from a fit to the six frequency channels and given in Figs. 6b, c respectively. The temporal evolution of the ELM event itself is represented in Fig. 6d by the envelope of magnetic fluctuations measured with a Mirnov probe. The ELM is characterized by a burst of fluctuations with overall duration of 1 ms resulting in a decrease of edge density and temperature gradients (not shown in the figure) and a fast particle and power flux across the last closed flux surface (also not shown). During the quiescent H-mode interval preceding the ELM event (t < 335.5 ms, (open circles in Fig. 5) the turbulence level is low and the spectral feature measured with Doppler reflectometry barely exceeds the receiver noise by +5 dB. The average Doppler shift scatters around 1.5 MHz corresponding an flux surface averaged $v_\perp$ = 20.5 km/s. With the onset of the ELM the total power received in the -1st order increases by a factor of 8 dB within a time interval of less than 50 μs. For individual channels the increase exceeds 15 dB. As the plasma remains turbulent the Doppler shift and thus $v_\perp$ decreases continuously to about 1 MHz (Fig. 6c, and Fig. 5, filled circles). A spin-up of $v_\perp$ to its H-mode value is observed on a timescale of 300 μs about together with the decrease of the turbulence level as the ELM event is over.

4. Conclusion

Doppler reflectometry has been proven to be a promising tool for the localized measurement of propagation velocity and wave number spectra of

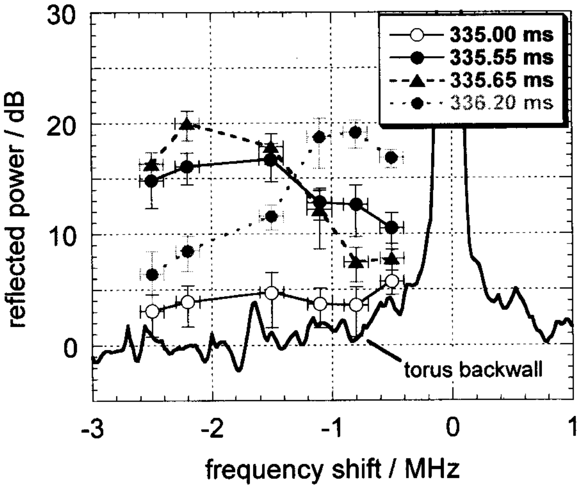

Fig. 5 Doppler reflectometry spectra measured via 6 bandpass filters at for different times during an ELM-event in W7-AS (reflecting layer about 2 cm inside the plasma boundary) The negative Doppler shift corresponds to propagation in electron diamagnetic direction. Note the log scale. The receiver background noise is included for comparison as measured with a spectrum analyzer and reflection from the torus backwall.

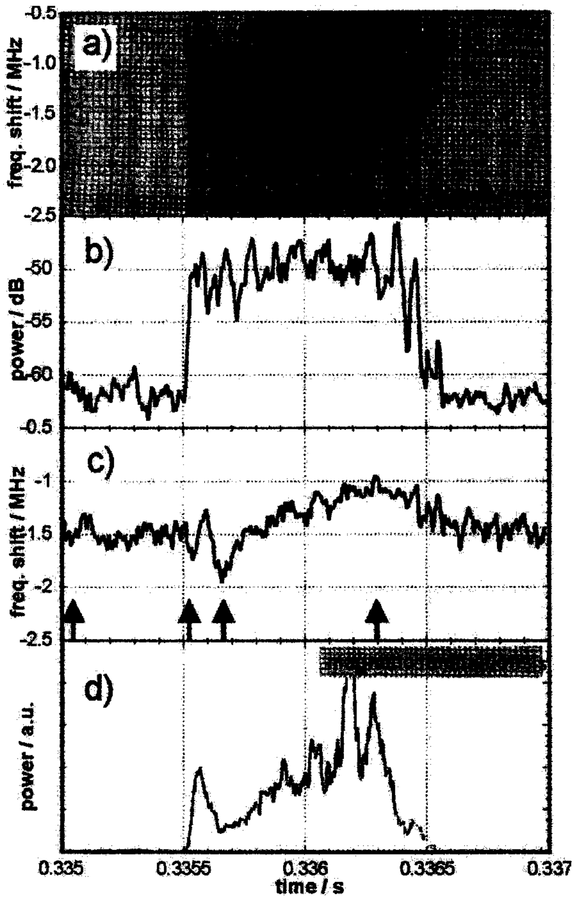

Fig. 6 Temporal evolution of Doppler reflectometry signals measured during an Edge localized Mode (ELM) event in W7-AS via bandpass filters as shown in Fig. 5: (a) contour plot of the spectra, (b) total power received in the -1st diffraction order, (c) frequency shift. The temporal evolution of the event is characterized in the lowest trace by the power of magnetic fluctuations measured with a Mirnov coil (d).

density perturbations. The measured Doppler shift is intrinsically linked to the propagation velocity $v_\perp$ in the direction perpendicular to the magnetic field independent on the poloidal and/or toroidal direction of the antenna tilt. First Doppler reflectometry results at W7-AS with variable θ_{tilt} show a broad K-spectrum within the accessible wavenumber range. The Doppler shift varies linearly with θ_{tilt}, i.e. the density perturbations propagate with a common group velocity $v_\perp$. During stationary phases the measured $v_\perp(r)$ is equal to $v_{E\times B}(r)$ within the error bars, indicating that the intrinsic phase velocity of the perturbations riding on the background plasma is small. Transient states of the plasma can be followed with a temporal resolution of < 50 μs. Thus Doppler reflectometry is well suited to investigate the interdependence of the turbulence spectrum and the propagation velocity respectively its shear.

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