Application of the microwave beam steering from poloidal correlation reflectometry for investigation of L-mode turbulence

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1. Introduction

Poloidal correlation reflectometry (PCR) is a powerful diagnostic to study the correlation of turbulent density fluctuations [1, 2]. In the typical application of PCR several poloidally and toroidally separated receiving antennas simultaneously measure the reflected beam from a cut-off layer in the plasma. Correlating the receiving antenna signals allows to determine the velocity, correlation length and life time of turbulent density fluctuations [3].

In this contribution an alternative application of the PCR diagnostic is proposed. All receiving antenna signals are combined in post-processing software with different phases to steer a total receiving beam in a given direction - thus operating as a steerable Doppler reflectometer. The measurement concept is based on a receiving phase array antenna (PAA) method, which has been tested on the MAST tokamak using the synthetic aperture microwave imaging (SAMI) system [4]. However in contrast to the SAMI system, here, only 4 receiving horn antennas are used, demonstrating that small and simple antenna clusters are enough for reasonable steering of the receiving beam. The application of the method to L-mode plasmas in ASDEX Upgrade (AUG) is presented and the quality of the synthetic beam discussed.

2. The practical algorithm and beam properties

The PCR antenna cluster at AUG [2, 3] consist of 1 transmitting and 4 receiving horn antennas, which have $\Delta y_j = (25, 50, 75, 100)$ mm separation in vertical (poloidal) direction and $\Delta x_j = (0, 50)$ mm in the horizontal (toroidal) direction respectively (see insert in fig. 1a). All antennas are aligned to the magnetic axis (i.e. normal incidence) and, therefore, the reflected (scattered) beam propagates back towards the receiving antennas. In the PAA method the combined effective receiving beam can be formed by a summation of all the receiving antenna signals with relative phase shifts. This can provide constructive interference from the desired direction and destructive interference from other directions. In the case of the PCR antenna cluster the steering of the combined receiving beam in vertical θ and horizontal ϕ directions is

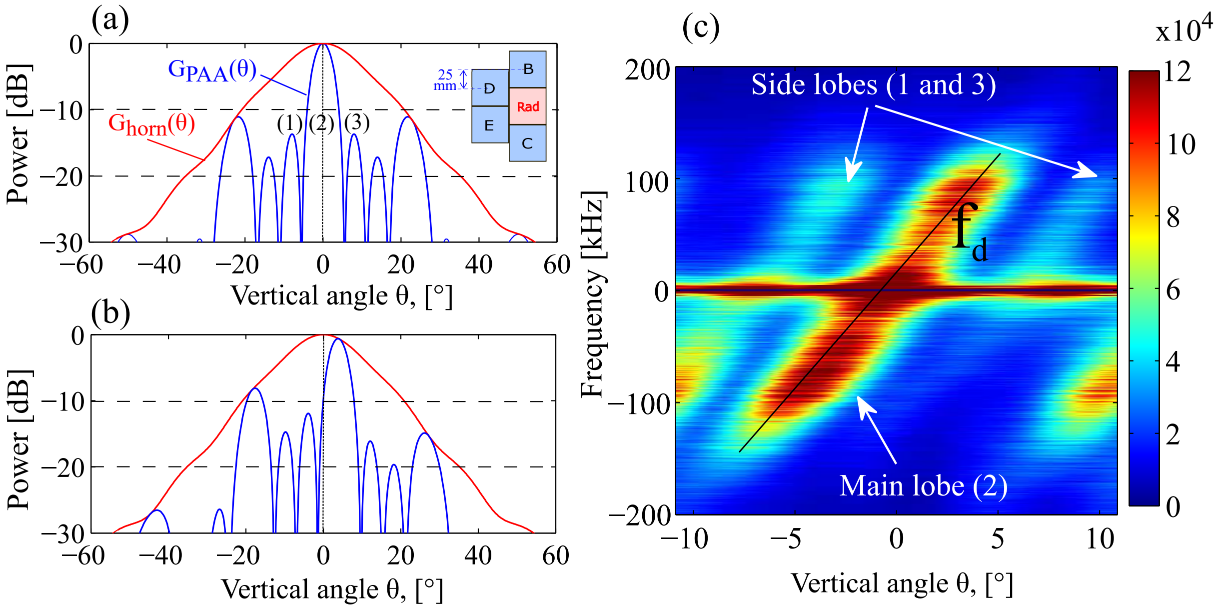

Figure 1: The gain of combined beam from PCR for (a) $\theta = 0°$, $\phi = 0°$ and (b) $\theta = 4°$, $\phi = 0°$. (c) The power spectra (color coded) of syntetic beam as function of vertical angle and frequency.

implemented by applying the following post-processing equation:

$$\begin{aligned} y_{sum}(\theta,\phi) &= \sum_{j=B,C,D,E} y_j \cdot e^{i\delta\psi_{Bj}(\theta,\phi)} \\ \delta\psi_{Bj}(\theta,\phi) &= k_0\left(\sin(\theta)\Delta y_{jB} + \cos(\theta)\sin(\phi)\Delta x_{Bj}\right). \end{aligned} \tag{1}$$

Here y_j are the complex signals of the receiving PCR antenna signals (B,C,D,E) and $\delta\psi_{Bj}$ the added phase between reference antenna (B) and the other antennas (B,C,D,E). k_0 is the vacuum wavenumber. Note that the phase delay in the different receiving waveguide paths needs to be compensated before the application of eqn. 1 (e.g. using cross-phase measurements between antennas). Fig. 1 shows an example of normal (a) and inclined (b) incidence synthetic beams from the PAA for f=31 GHz. Here the gain of combined beam is calculated as $G_{PAA}(\theta,\phi) = G_{horn}(\theta,\phi) \cdot G_{iso}(\theta,\phi)$, where G_{horn} is the gain of a single horn antenna and G_{iso} the gain of the combined isotropic radiators calculated using a matlab package [5]. The 3dB half beam width and maximum steered angle of a total combined beam are calculate as

	30 GHz	45 GHz	60 GHz
Half Beam width	$\delta\theta = 1.8°$, $\delta\phi = 2.7°$	$\delta\theta = 1.2°$, $\delta\phi = 1.8°$	$\delta\theta = 0.9°$, $\delta\phi = 1.5°$
Maximal angle	$\theta_m = 10.5°$, $\phi_m = 5°$	$\theta_m = 8°$, $\phi_m = 3.6°$	$\theta_m = 5.6°$, $\phi_m = 2.7°$

The beam width of PAA is reduced by factor of 4 compared to original horn antenna. The maximum steering angle is limited by the grating lobes of the PAA [5], which can be improved in the future if the parameter $k_0 \cdot d$ is minimized, where d is the minimal separation between antennas.

3. Velocity measurement and influence of magnetic field pitch angle

Fig. 1c shows the measured spectra $S(f)$ of the combined PAA signal as a function of the vertical (poloidal) angle from discharge #31427 at $\rho_{pol} = 0.985$ (E_r well region). The Doppler shift f_d is well separated from zero frequency for $|\theta| > 3^\circ$ and inverts sign for positive and negative angles. It is interesting to note that the small contribution of side lobes is also observable, which are located approximately at the points predicted in fig. 1a. The PAA grating lobes, however, are not observed, probably due to the strong attenuation of backscattered signals at higher angles. Fig. 2 shows the estimation of the Doppler frequency $f_d = \max(S(f))$ as a function of both vertical and horizontal angle. In calculating f_d the DC component of the signal was filtered out using high pass filter (>5 kHz). f_d is not symmetric in the toroidal plane due to the influence of the magnetic field pitch angle. Indeed, since a parallel wavenumber of the turbulent density fluctuations is small, $k_{||} \approx 0$, the Doppler shift is sensitive to the perpendicular wavenumber only ($f_d = k_\perp v_\perp/(2\pi)$). Fig. 2b shows the calculated $k_\perp$ using the TorBeam beam tracing code [6], where the same symmetry as in fig. 2a is observed. This opens a new method to measure the magnetic field pitch angle at AUG, which should be compared with the method used in [2].

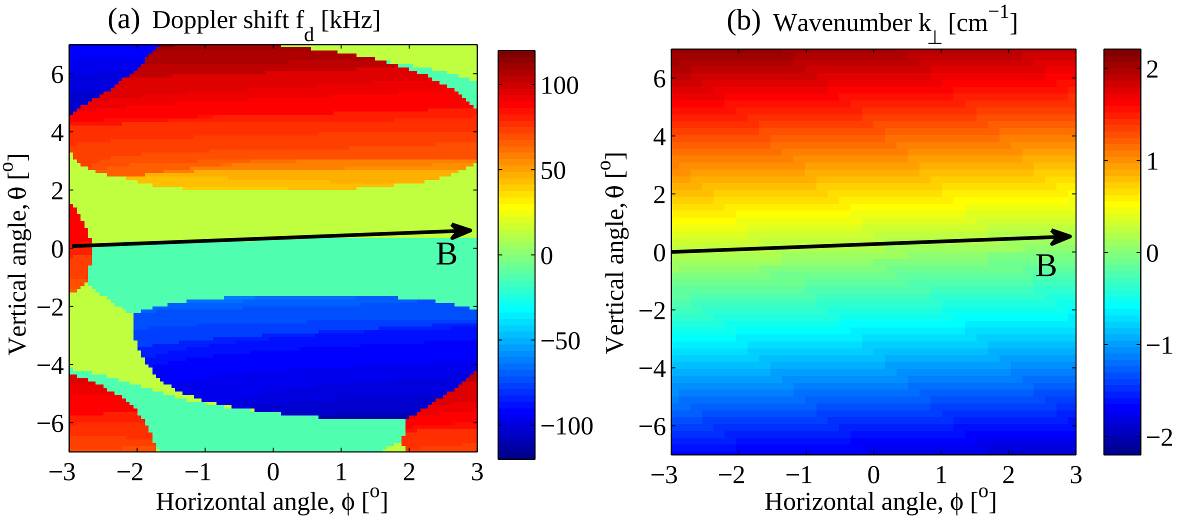

Figure 2: (a) The measured Doppler frequency as function of vertical and horizontal angles. (b) Scattering perpendicular wavenumber from the TorBeam code.

Using the measured f_d and calculated $k_\perp$ the perpendicular velocity profile $v_\perp = 2\pi f_d/k_\perp$ has been estimated in fig. 3 for the case of $\theta = 6^\circ$, $\phi = 0^\circ$ (black points). The velocity sign change from the edge to the core is due to the contribution of intrinsic toroidal velocity. The gap in the profile corresponds to the region where the Doppler frequency cannot clearly be separated from the zero frequency contribution. However, the separation of f_d was possible for V-band Doppler reflectometry measuring at higher $k_\perp \approx 10$ cm^{-1} [7] as shown by blue line, where good agreement is observed confirming the study in [2] that the velocity does not depend on $k_\perp$.

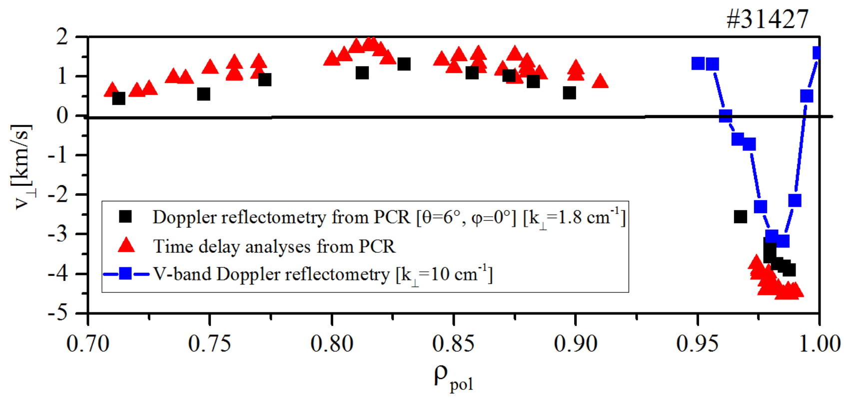

Figure 3: Comparison of calculated velocity using different methods.

The measured velocity is compared also with the traditional PCR time delay analyses [2] (red points). Here, a small difference ($\approx$ 0.5 km/s) is observed, which might be a result of a transition to a strong turbulence regime [8]. This will be investigated in the future in more details.

4. Discussion and conclusion

The steering of the receiving beam in both vertical ($\theta = \pm 10^\circ$) and horizontal ($\phi = \pm 5^\circ$) directions has been demonstrated using the PCR antenna cluster installed at AUG, allowing the PCR diagnostic to operate as a Doppler reflectometer covering perpendicular wavenumbers $k_\perp \approx \pm 3$ cm^{-1} with $\Delta k_\perp \approx 0.5$ cm^{-1}. The method is robust and can be applied to every AUG discharge. The calculated velocity from the Doppler shift is in agreement with results obtained from a fixed tilt V-band Doppler reflectometer and show only a 0.5 km/s difference compared to time-delay analyses.

The maximum steering angle is limited by the PAA grating lobes depending on the minimal separation, while the width of the beam depends on the number of antennas. This information can be used to further optimize the antenna cluster for beam steering purposes. The presented method can be used to measure the magnetic field pitch angle α, the dispersion relation $v_\perp(k_\perp)$ and the turbulent wavenumber spectrum $\delta n_k^2(k_\perp)$. The method may also be important for comparison of frequency dependent with wavenumber dependent techniques as discussed in [8].

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