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Phase contrast imaging for the measurements of microturbulence

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The microturbulence is one of the most important physics quantities for the investigation of turbulence driven anomalous transport of magnetically confined plasma. The phase contrast imaging (PCI) is one of the powerful turbulence diagnostics. This technique was first applied to measure transparent biological cell [1]. Then, the use of laser enabled the visualization of plasma jet [2] and measurements of microturbulence in magnetically confined plasma [3]. The phase contrast imaging makes use of the Raman-Nath diffraction regime, which is determined for light scattering on acoustic waves [4]. Usually, infrared laser around 10μm wavelength is used as a radiation source for the turbulence measurements of high temperature plasma. The injected laser wavefront is modulated in phase by the modulation of refractive index of electron density due to the turbulence. Then scattered and non-scattered beam are focused by the same focusing optics. At the lens focal plane, focusing position of scattered and non-scattered components are different. By using optical plate, the π/2 phase difference can be given between scattered and non-scattered components. This process exchanges from small phase variation to small intensity variation in the image of turbulence wave. By using a liquid nitrogen cooled detector, small intensity variation can be measured with good accuracy. This process is possible for the fluctuation, of which scattered and non-scattered components are clearly separated. However, one of the issues of this diagnostics are spatial resolution along the injected beam axis. For the ion scale turbulence, of which wavelength is several millimeter ~ several centimeter in present toroidal devices, the length of the scattering volume becomes several meter, and no-spatial resolution is obtained along the beam axis. We decided therefore to use the following approach for the Large Helical Device (LHD). There are important characteristics of turbulence and LHD. Firstly, there is a strong asymmetry of the turbulence wavenumber parallel and perpendicular to the magnetic field. The perpendicular wavenumber is much larger than parallel wavenumber, thus, turbulence propagates perpendicular to the magnetic field. Secondly, the magnetic field vector rotates along the injected beam axis due to the magnetic shear. In LHD, the angle changes around +- 50 degree. Then, integrated picture along beam axis becomes grid structure [4]. We measure the integrated picture by using a 6 by 8 channels two-dimensional detector [5]. Then, the integrated picture is deconvoluted by two-dimensional Fourier transform [5]. We applied the maximum entropy method in order to get good wavenumber resolution [6]. The turbulence propagation direction is perpendicular to the local magnetic field vector. The magnetic field vector can be obtained from plasma equilibrium data and its spatial location is obtainable. Thus, the determination of propagation direction provides spatial location of turbulence. This technique is called two-dimensional phase contrast imaging (2D-PCI). The spatial resolution is around 10~30% of the minor radius. This is much more modest compared with microwave reflectometry, of which spatial resolution can be 1 % of minor radius at the edge density gradient region. However, 2D-PCI can provide instantaneous turbulence profiles in the almost entire region of plasma cross section. Also, accessibility to plasma is excellent. The data is obtainable for any discharge condition at higher than line averaged density ~$0.5 \times 10^{19} m^{-3}$ in LHD

Essential results are obtained by using a 2D-PCI in LHD. The ion temperature gradient turbulence was identified from the comparison with gyro-kinetic linear and non-linear simulations [7,8]. The isotope effects of turbulence, where turbulence amplitude was lower in deuterium than in hydrogen plasma, were found [9]. Turbulence spreading from core to scrape off layer with reduction of divertor heat flux was found [10]. Improvement of confinement associated with reduction of turbulence with Boron powder injection was found [11]. Turbulence transition from trapped electron mode to ion temperature gradient mode associated with switching from isotope non-mixing to isotope mixing [12].

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