Development of Glass-Tube-Pair Type Doppler Probe Array for 1D Profile Measurement of Two Component Ion-Flow Vector

Ryo SOMEYA, Haruaki TANAKA, Yugo FUNATO, Yunhan CAI, Moe AKIMITSU, Hiroshi TANABE and Yasushi ONO

Graduate School of Frontier Sciences, The University of Tokyo, Tokyo 113-0032, Japan

(Received 12 April 2021 / Accepted 25 April 2021)

We developed a new glass-tube-pair type Doppler probe array for 1D ion velocity vector and temperature measurement. It needs just two parallel glass-tube insertion, realizing low plasma perturbation and 1D ion flow vector measurement on a single discharge. Using four mirrors and optical fibers for one measurement point, this system can measure ion local light emissions of each measurement volume from four different directions, enabling us to measure local ion flow vector and temperature. All set of mirrors and optical fibers are aligned in the two parallel glass tubes for 1D measurement by a single discharge. This system measured successfully ion outflow speed of two merging tokamak plasmas, about 80% of poloidal Alfvén speed in agreement with recent reconnection experiments and theory.

Keywords: ion flow measurement, Doppler spectroscopy, magnetic reconnection, tokamak merging, outflow

DOI: 10.1585/pfr.16.1202078

For ion temperature and flow measurements, Doppler spectroscopy has been widely used both in laboratory experiments and in space observations [1–3]. Using the line spectrum emitted from ions, we can measure Doppler spectrum profile in the line of sight by means of which line-averaged ion temperature and velocity component can be calculated. Since the emitted light is integrated along the view-line, some tomographic reconstruction [4] or local measurement by probes is required to calculate local ion temperature and velocity. The former method already enabled us to measure ion temperature profile successfully by using tomography techniques but it is still difficult to reconstruct local ion flow. On the other hand, the MRX group in Princeton University has developed the IDS probe [5], which can measure local ion velocity, but it can measure only one point for a single discharge, which is unfavorable for measurement of profile in non-steady and unreproducible phenomenon as magnetic reconnection. It is noted that its size is about 6 times larger than measurement area, causing large plasma perturbation. Then, an important question arises as to whether we developed a new type of Doppler probe which realizes both 1D local ion temperature and velocity vector measurement by a single discharge and low plasma perturbation.

Figure 1 (a) shows the internal structure of our new Doppler probe array and the optical system. This probe array need insertion of just two straight glass tubes (the inner diameter is 8 mm, the outer diameter is 10 mm) for 1D ion flow and temperature measurement. Its probe volume per channel is about 8% of the IDS probe, indicating its plasma perturbation much less than the IDS probe's one [5]. Furthermore, the size of each measurement area is 3.2 cm × 2.0 cm × 1.0 cm, indicating that spatial resolution is improved by 2.5 times. Each area is surrounded by 4 flat mirrors (3 mm × 3 mm × 1 mm). As shown in Fig. 1 (b) in detail, the four optical fibers (the diameter of the clads is 500 μm) receive emitted lights from two pairs of view-lines (1-A & 1-B, 1-C & 1-D). For 1D measurement, four sets of mirrors and optical fibers mentioned above are aligned at intervals of 5 cm in the two parallel glass tubes, forming 4 × 4 view-lines in total. Then, 4 × 4 optical fibers

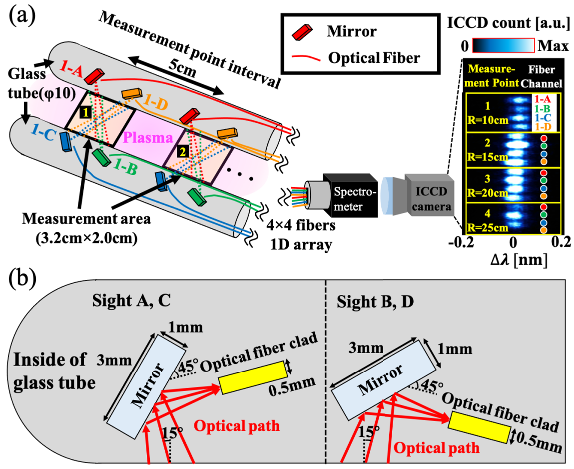

Fig. 1 (a) Schematic view of Doppler probe array with two-pairs of view-lines and the optical system, (b) layout of the mirror and the optical fiber in glass tube and the optical path.

author's e-mail: rsomeya@ts.t.u-tokyo.ac.jp

are led to a spectrometer separately in a line and finally to an ICCD camera (Andor DH334T 18F-03: QE = 18%) for line spectra measurements [1]. The ICCD image in Fig. 1 (a) shows the measured 4 × 4 spectra of Ar II line (480.6 nm). Since Doppler shifts of each pair of spectra are caused by ion velocity component in each line of sight, the local ion velocity vector can be calculated from the two velocity components (A to B and C to D). In general, frequent calibration of spectrometer is required for accurate measurement of Doppler shift because the shift depends on non-shifted peak which cannot be observed during measurement of flow. However, if we calculate Doppler shift from bi-directional measurement of line spectrum, we can significantly decrease the calibration error of the Doppler shifts. All mirrors and fibers in the glass tubes are supported by 3D printed mirror holders to fix at exact positions.

The Doppler probe array was tested in a TS-6 device [6], whose cylindrical vacuum vessel has a diameter of 0.75 m and a length of 1.44 m and two internal Poloidal Field coils are set inside. Two Spherical Tokamaks (ST) are produced by the induction of two PF coils. When the two PF coil currents reverse, the two STs are fully pinched off from them, move toward the mid-plane to merge together.

Figure 2 (a) shows the experimental setups of Doppler probe array in a TS-6 device. We inserted two glass tubes with the Doppler probe array into the vacuum vessel radially to measure radial profile of ion flow and temperature on $R - Z$ plane. We changed the probe insertion ports in the Z direction to measure two radial profiles. Figure 2 (b) shows radial profiles of ion velocity vectors with errors about 10% along $Z = 2.1$ cm and $Z = -2.1$ cm and poloidal flux contours. The single ST plasma moving in Z direction was used to calibrate the plasma flow in Z direction. Figure 2 (c) shows radial profiles of ion temperature along $Z = 2.1$ cm and $Z = -2.1$ cm. The ion gyro-radius was about 1 cm in the present merging operation.

It is clear that the measured ions flow speed is as slow as 5 ~ 40% of the poloidal Alfvén speed in early stage of reconnection, namely in 463 μs ~ 465 μs. Then, at 467 μs, ions were drastically accelerated up to 11.6 km/s which equals to 80% of Alfvén speed. In the previous ST merging experiment, it was reported that reconnection outflow speed was equal to 70 ~ 80% of Alfvén speed [7] and also in magnetosphere measurements, it was reported that outflow speed was equal to about 75% of Alfvén speed [8]. Our results are consistent with these reports.

Meanwhile, ion temperature increased gradually with the rate of 5 eV/μs, in rough agreement with the previous research [7]. The measured temperature often depends on the view-lines, probably due to the non-Maxwellian ion velocity distribution observed in PIC simulations [9]. Thus, our next issue will be the velocity distribution measurement for more precise understanding of ion motion during

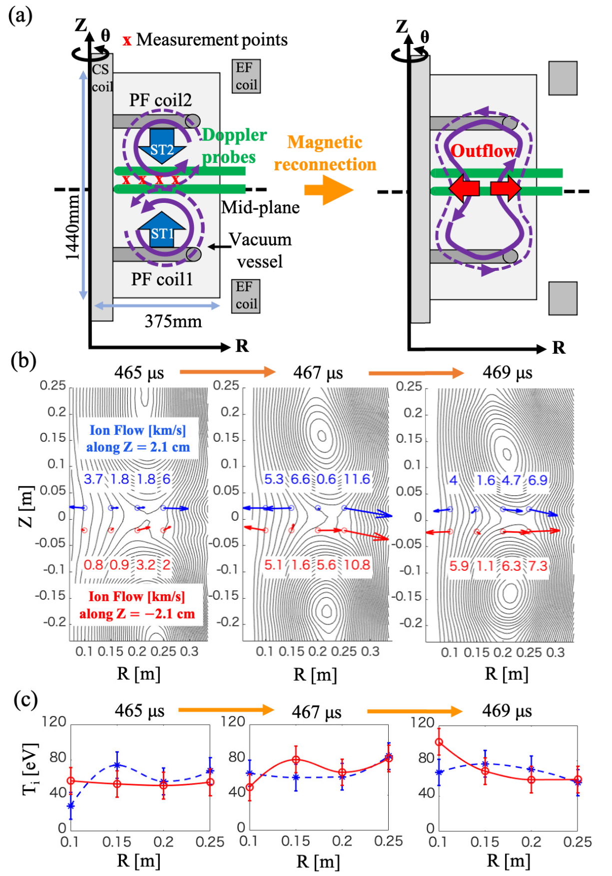

Fig. 2 (a) Schematic view of magnetic field lines and plasma flows of two merging ST plasmas in TS-6 [6], (b) radial profiles of ion velocity along $Z = 2.1$ cm (blue allows) and along $Z = -2.1$ cm (red allows) and poloidal flux contours, (c) radial profiles of ion temperature along $Z = 2.1$ cm (blue lines) and along $Z = -2.1$ cm (red lines).

magnetic reconnection.

In summary, we developed a new Doppler probe array for 1D profile measurement of two component ion flow vector and temperature, which needs just two parallel glass tube insertion. Its advantage is the first 1D profile measurement of ion flow vector with low plasma perturbation. As the first test of the probe array, we made successfully the 1D profile measurement of ion velocity and temperature during magnetic reconnection in agreement with the previous research.

[1] H. Tanabe *et al.*, Nucl. Fusion **53**, 093027 (2013).
[2] H. Hara *et al.*, Astrophys. J. **741**, 107 (2011).
[3] M. Mayor *et al.*, Nature **513**, 328 (2014).
[4] A.L. Balandin and Y. Ono, Eur. Phys. J. D **17**, 337 (2001).
[5] A. Kuritsyn *et al.*, Rev. Sci. Instrum. **77**, 10F112 (2006).
[6] H. Tanabe *et al.*, Nucl. Fusion **59**, 086041 (2019).
[7] Y. Ono *et al.*, Phys. Rev. Lett. **107**, 185001 (2011).
[8] T.D. Phan *et al.*, Geophys. Res. Lett. **41**, 7002 (2014).
[9] S. Usami *et al.*, Phys. Plasmas **26**, 102103 (2019).