Response to "The invalidity of a Mach probe model" [Phys. Plasmas 9, 1832 (2002)]

Shunjiro Shinohara
Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga, Fukuoka 816-8580, Japan

(Received 9 October 2001; accepted 31 January 2002)

[DOI: 10.1063/1.1464887]

In the Comment entitled "The invalidity of a Mach probe model" by I. H. Hutchinson, no existing reliable theories for unmagnetized probes were mentioned, in addition to inappropriate use of the Hudis and Lidsky[1] model. Although his general opinion on the unmagnetized probe theory is correct, we wish to emphasize our reasonable consideration discussed below.

In our recent paper,[2] which was cited by him as one of examples of inappropriate citation of Ref. 1, radial profiles of the azimuthal rotation velocity was presented in Fig. 3 of Ref. 2 (note that he did not comment on our experimental result itself in the main body: establishment of strong velocity shear and plasma density profile modification with associated low frequency fluctuations). Here, in our condition, ion Larmor radius was larger than a probe size (unmagnetized case), and this velocity was derived from Ref. 1 and also from Ref. 3 (Hutchinson is a co-author), and both of which showed nearly the same coefficient in estimating flow velocity in our case. We recognized the difficulties in estimating the absolute and fast flow velocity, especially the perpendicular flow (azimuthal direction in a cylindrical geometry) instead of the parallel one, where the one-dimensional model was discussed by him. Therefore, we carefully treated this issue using expressions in our paper as follows.

Although there are a number of theories, e.g., Refs. 26–28 (N.B.: here in this response, Refs. 1, 4, and 3), on estimating the plasma flow parallel to the magnetic field and trials on estimating the azimuthal (perpendicular) flow, e.g., Refs. 29 and 30 (N.B.: here, Refs. 5 and 6), it is difficult to estimate the correct value of M (N.B.: Mach number, azimuthal rotation velocity normalized by ion sound velocity) in the perpendicular direction. Here, for convenience, an unmagnetized model (Ref. 26) or a kinetic model (Ref. 28) with zero viscosity (N.B.: here, these correspond to Refs. 1 and 3, respectively) was employed; $K \sim 1.26$ for both cases, where $M=(1/K)\ln R$ (R: ratio of the probe current facing upstream to downstream).

In addition to this careful expression, in our paper, the absolute values of flow velocity were neither crucial nor a main story as stated before; this very high velocity (here, M is estimated to be in the region of 1) was a measure of, in a sense, relative velocity but the obtained velocity with a coefficient of $K \sim 1.26$ seemed to be close to a real value, which was suggested by Hutchinson as to mentioning fairly good agreements in many cases. This was also confirmed by preliminary Doppler measurement by the use of our monochromator.

Most people engaging this flow measurement including Mach probe techniques are aware of the difficulty in estimating a real flow velocity due to the fact that a definite, correct probe theory has been established so far in only very limited conditions/assumptions. By improving weak points step by step, trying to establish a unified theory including numerical simulation studies is crucial and extending a work in three-dimensional geometry as well as in the high velocity region of $M>1$ in the perpendicular direction with respect to the magnetic field is strongly needed.

In summary, we would like to point out that, in estimating flow velocity in our paper, we carefully used the above practically useful formula with $K \sim 1.26$ in our condition from Refs. 1 and 3, for convenience, due to the absence of an established theory as he mentioned. In addition, very high, steady flow velocity could be ascertained, and our experimental (physics) results such as the fast plasma flow, the profile modification and fluctuations were unchanged.

[1] M. Hudis and L. M. Lidsky, J. Appl. Phys. **41**, 5011 (1970).
[2] S. Shinohara, N. Matsuoka, and S. Matsuyama, Phys. Plasmas **8**, 1154 (2001).
[3] K-S. Chung, I. H. Hutchinson, B. LaBombard, and R. W. Conn, Phys. Fluids B **1**, 2229 (1989).
[4] P. C. Stangeby, Phys. Fluids **27**, 2699 (1984).
[5] B. J. Peterson, J. N. Talmadge, D. T. Anderson, F. S. B. Anderson, and J. L. Shohet, Rev. Sci. Instrum. **65**, 2599 (1994).
[6] R. Hatakeyama, N. Hershkowitz, R. Majeski, Y. J. Wen, D. B. Brouchous, P. Proberts, R. A. Breun, D. Roberts, M. Vukovic, and T. Tanaka, Phys. Plasmas **4**, 2947 (1997).

