Simultaneous Enhancement of Core Electron Density and Temperature by Synergistic Effect of Molecular Beam Injection and Shock due to Toroidal Flow

X. M. Qiu, H. B. Jiang, L. H. Yao

Southwestern Institute of Physics, P. O. Box 432, Chengdu 610041, China

e-mail contact of main author : xmqiu@swip.ac.cn

Abstract. Synergistic effect of supersonic molecular beam injection and shock wave due to toroidal flow is suggested to enhance both the core electron density and temperature in tokamaks, based on a shock equation we have derived. It relates the ratio of temperature on either side of the shock with the ratio of density on either side, the Mach number of the toroidal flow and the poloidal beta of tokamaks. It is found that when $M \geq M_c$ (the critical Mach number) the synergistic effect of supersonic molecular beam injection and shock wave due to toroidal flow can make both the core electron density and temperature enhance. The ratio of temperature on either side of the shock wave against M at different values of the poloidal beta is plotted.

1. Introduction

The control of plasma density is an issue that continues to pose great problems. Looking back on the history of tokamak progress, one sees that the plasma density in present large devices is only two or three times higher than that of the earliest devices. Therefore in the opinion of International Thermonuclear Experimental Reactor (ITER) physics expert group, the fuelling in the coming ITER device is a big physics problem, the key in which consists in how making the fuel penetrate ITER plasma edge to enter into its high-temperature core [1]. The common fuelling techniques (such as gas puffing, ice pellet injection) are difficult to be competent at this task. Supersonic molecular beam injection (SMBI) has been successfully developed and used in the HL-1M tokamak [2]. Recently, in the high performance experiments on high pressure SMBI in that device, the plasma line averaged electron density increases from 0.77×10^{13} to $5.67 \times 10^{13} \mathrm{cm}^{-3}$ [3], increasing by 736%. In the meantime, however, the core electron temperature T_e decreases because of the density peaking and thus the hollow profile of electron temperature [4]. Therefore it needs to use another method for enhancing the T_e.

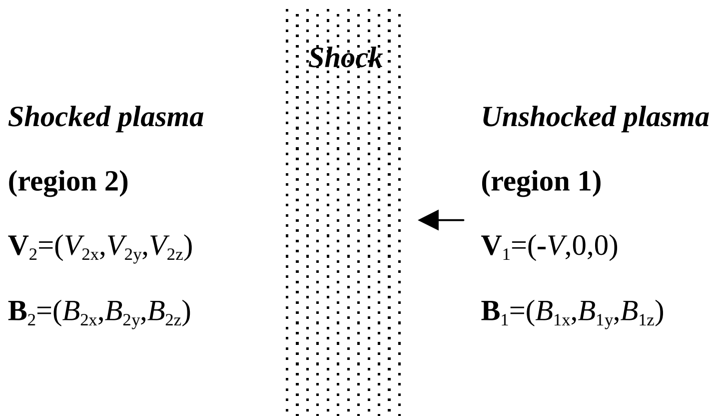

FIG.1 Schematic diagram of shock wave

As well known, the toroidal flow $\mathbf{V}_1$ in tokamaks can not only improve plasma confinement but also give rise to shock wave; only the study on toroidal shock wave is not as wide as poloidal one [5]. And the toroidal flow $\mathbf{V}_1$ in tokamaks can be applied or generated self-organizationally by plasma. When V_1 exceeds local sound velocity c_s, plasma perturbations caused by the moving V_1-front will propagate slower than the V_1-front and thus accumulate continuously in front of the V_1-front to form shock wave. The shock wave moves upstream in the form of a plane shock front, as shown in Fig. 1, where regions 1 and 2 represent the unshocked and shocked plasma, respectively.

2. Results

We have derived a shock equation (see Ref. 6). Now on the assumption that the value of ratio T_i/T_e (T_i represents the core ion temperature) in region 1 on Fig. 1 is the same as in region 2, this equation becomes

$$\frac{T_{e2}}{T_{e1}} = 1 + \frac{(\gamma - 1)}{2\gamma}[\gamma M^2 (1 - \frac{1}{r^2}) - \frac{4(r-1)}{\beta_p}], \quad (1)$$

where the shock strength $R \equiv P_2/P_1 = rT_{e2}/T_{e1}$ [$P_{1(2)}$ being the core plasma pressure in region 1 (2) on Fig. 1] and $r \equiv \rho_2/\rho_1$ = n_{e2}/n_{e1} with $n_{e1(2)}$ being the core electron density in region 1 (2) on Fig. 1; the Mach number $M \equiv V_1/c_{s1}$; γ is the ratio of specific heat; $\beta_p \equiv 8\pi P_1/B_1^2$ is the poloidal beta of tokamaks in region 1. In Ref. 6 we have shown that the toroidal magnetic field parallel to the shock propagation plays no role in the present shock problem.

As stated above, in the presence of SMBI, definitely $r > 1$. Therefore, from Eq. (1) we can see that the second term ($\propto M^2 \propto$ the kinetic energy of the toroidal flow) on its right-hand side enhances the ratio T_{e2}/T_{e1} and the third term [$\propto 1/\beta_p$ and $\propto (r-1)$] depresses the ratio. In other words, physically equation (1) is very reasonable, in spite of that it has been obtained under three approximate assumptions. They are: (a) The plasmas on either side of the shock are assumed to be perfect. (b) The shock front thickness is very thin. So it might as well assume there is not enough time for the non-adiabatic processes (such as heat conduction) to occur inside the shock layer. (c) It is assumed that the value of ratio T_i/T_e in region 1 is the same as in region 2. In the following analysis, we choose $r = 5$ and $\gamma = 5/3$ as usual. From Eq. (1) we obtain the critical Mach number M_c making $T_{e2}/T_{e1} = 1$

$$M_c = 2r/\sqrt{\gamma\beta_p(r+1)} . \quad (2)$$

For $r = 5$, $\gamma = 5/3$, and $\beta_p = 3$ we find $M_c = 1.8$. That is, when $M \geq M_c$ the synergistic effect of SMBI and shock wave due to toroidal flow can make both the core electron density and temperature enhance. Equation (2) shows that the higher β_p the lower the critical Mach number. That is, for coming high-β_p tokamaks, it is easier to achieve that the synergistic effect of supersonic molecular beam injection and shock wave due to toroidal flow makes both the core electron density and temperature enhance. Figure 2 plots the T_{e2}/T_{e1} against M for $r = 5$ and $\gamma = 5/3$ at different β_p values. We see that for any β_p value, the ratio T_{e2}/T_{e1} increases with toroidal flow pretty rapidly.

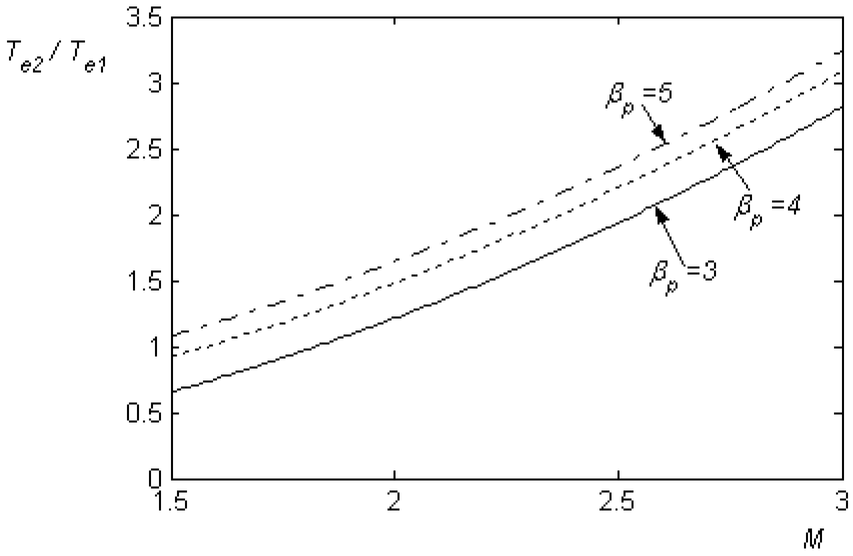

FIG. 2 T_{e2}/T_{e1} *vs* M *for* $r = 5$ *and* $\gamma = 5/3$ *at different* β_p *values*

3. Conclusions

In conclusion, at first one expects the toroidal flow in tokamaks to improve plasma confinement; but once this goal attains, it will be unnecessary that the toroidal flow continues to leave in the system. Therefore it is desirable to make the kinetic energy of the toroidal flow convert to the thermal energy of plasma in some form. The present work devotes a theoretical analysis to it. The conversion of the kinetic energy of toroidal flow to the thermal energy of plasma in the form of shock wave proposed in the present paper is very suitable for coming high-β_p tokamaks, because from Eq. (1) the higher β_p the larger T_{e2}/T_{e1} .

Acknowledgements

This work was supported by the National Natural Science Foundation of China under Grant No. 10075014. The authors would like to thank Dr. A. K. Wang and Dr. J. Q. Li for their helpful discussion in toroidal flow.

References

[1] ITER Physics Expert Group on Divertor et al., Nuclear Fusion, **39** (1999) 2416-2422.
[2] LIANGHUA YAO et al., Nuclear Fusion, **38** (1998) 631.
[3] LIANGHUA YAO et al., Nuclear Fusion, **44** (2004) 420.
[4] LIANGHUA YAO et al., Acta Physica Sinica, **51** (2002) 596 (*in Chinese*).
[5] K. C. SHAING, H. D. HAZELTINE, H. SANUKI, Phys. Fluids B **4** (1992) 404.
[6] X. M. QIU et al., Role of on-board discharge in shock wave drag reduction and plasma cloaking, Chinese Phys., *in print* (2006).