PLASMA-NEUTRAL MOMENTUM EXCHANGE AND ITS APPLICATIONS TO EDGE LOCALIZED MODE AND TOROIDAL ROTATION ON TOKAMAKS

Kwan Chul Lee
Korea Institute of Fusion Energy
Daejeon, Korea
Email: kclee@kfe.re.kr

Abstract

Analysis of ion-neutral momentum exchange explained electric field formations not only for the tokamak boundary but also for the arc discharge and earth ionosphere [1]. The electron-neutral momentum exchange can play an important role when the plasma is accelerated in an electric field such as ohmic discharge of tokamaks. It is found that the strong electric fields of ionosphere such as black aurora and tokamak edge are induced by the ion-neutral momentum exchange. Another similarity between black aurora and tokamak edge is that there are circular structure which are occurring periodically with ExB drift.The unbalanced momentum exchange between plasma and neutral can generated the intrinsic rotation. Intrinsic rotation measurement on KSTAR agreed well with analysis by plasma-neutral interaction.

1. INTRODUCTION

Among the most important risks of ITER operation, number one is the disruption, the second is the uncertainty of High confinement mode (H-mode) transition, and the third is the Edge Localized Modes (ELMs). Despite all the effort made since 1950s, these major obstacles remains yet to be overcome. The plasma-neutral interaction is a key underlying mechanism that can solve these problems. Many obstacles in the plasma physics are due to the lack of understanding on the electric field and current in it. It is said that more than 99% of whole universe is consist of plasmas. And most of these plasmas include a region where the plasma is not fully ionized so that there are significant amount of neutral particles (atoms and molecules). The neutral aspect of plasma physics is dealing with the consequences of neutrals in the plasmas as they interact with charged particles. And surprisingly many mysterious phenomena of plasma can be analysed by this approach. There are at least four important reactions when plasmas include significant amount of neutrals which are ionization, recombination, charge exchange and elastic scattering. Ionization and recombination must be included when the number of particles is to be calculated since these reactions act as source and sink of the plasma particles. For the charge redistribution, reactions between ion and neutral (such as ion impact ionization, charge exchange, ion-neutral elastic scattering) are more important than reactions between electron and neutral (such as electron impact ionization and electron-neutral elastic scattering) since the electron-neutral collisions make less momentum exchange due to the large mass difference. So these electron-neutral reactions will be often but not always neglected in the discussions of current. The rate of ion impact ionizations is relatively low for most examples of this paper and the effect of ion-neutral elastic scattering is very similar to the charge exchange so sometimes reactions between ion and neutral are represented by just charge exchange. A charge exchange reaction occurs when two particles (mostly one ion and one neutral) are closely encountering and an electron from one particle changes its ride to the other particle. So for the case of ion-neutral charge exchange of same species, it also exchanges their identity, which means their momentum exchange is maximized. Although the charge exchange is emphasized by this reason throughout this paper, it should be pointed out that all the reactions must be included for the complete calculation of particle and energy transport. One general excuse for not paying attention to the plasma interaction with neutrals in the plasma physics is so called “collisionless plasma”. Plasmas can be sorted by two categories; highly collisional cases and collisionless cases. The fluid equations are used for the collisional plasmas and the kinetic equations are used for the collisionless plasmas. Although both approach methods have been well developed with great effort, sometimes neither of them is good enough to explain the observations in plasmas. In fact those plasmas sorted as collisionless still have a little of collisions. What we have missed is that this small number of collisions can make a big difference. For example at the boundary of tokamak the ion-neutral charge exchange mean free path is about hundreds times larger than the scale of plasma and the neutral density is thousands times smaller than the plasma density. With this circumstance one can easily think that if the collision is important it should be the Coulomb collisions among charged particles since the collisions with neutrals are so rare! Actually very important collisions among plasma charged particles were found in tokamak; those collisions between trapped particles and passing particles. The neo-classical theory has been developed based on these collisions [2]. Neo-classical theory explains certain phenomena but unfortunately it showed its limit too. The content of this paper shows how those rare occasions of ion-neutral collisions can make a big difference. After the summary of Gyro-Centre Shift analysis, application of plasma-neutral interaction to the similarity of the black aurora and the ELMs is discussed in section 3, and the intrinsic rotation is analysed in section 4 followed by the conclusions.

2. ELECTRIC FIELD FORMATION BY PLASMA-NEUTRAL INTERACTION

As shown in the figure 1, boundary region of fusion device has narrow overlapping area of the plasma particles and neutrals, where the charge exchange reactions occur. As illustrated, the centre of ion gyro-motion is shifted after the charge exchange reaction. This shift is proportional to the gyro-radius so the electron gyro-centre shift is negligible so when the ion has one direction drift, this Gyro-Centre Shift (GCS) separates the charge and forms electric field. The driving mechanism of one directional ion movement is ion drift. There are three important components in ion drift which are ExB drift, ion diamagnetic drift, and the ion drift induced by the neutral density gradient. Actually, the ExB drift is the reaction of the GCS current for the E-field formation process. At the beginning, there is no E-filed and two other terms drive GCS current to separate the charge. As time goes by, E-field is formed and ExB drift compensates the other two drifts. So the gradients of plasma pressure and the neutral density generate the charge separation and the E-field keeps the balance of three terms as the steady state.

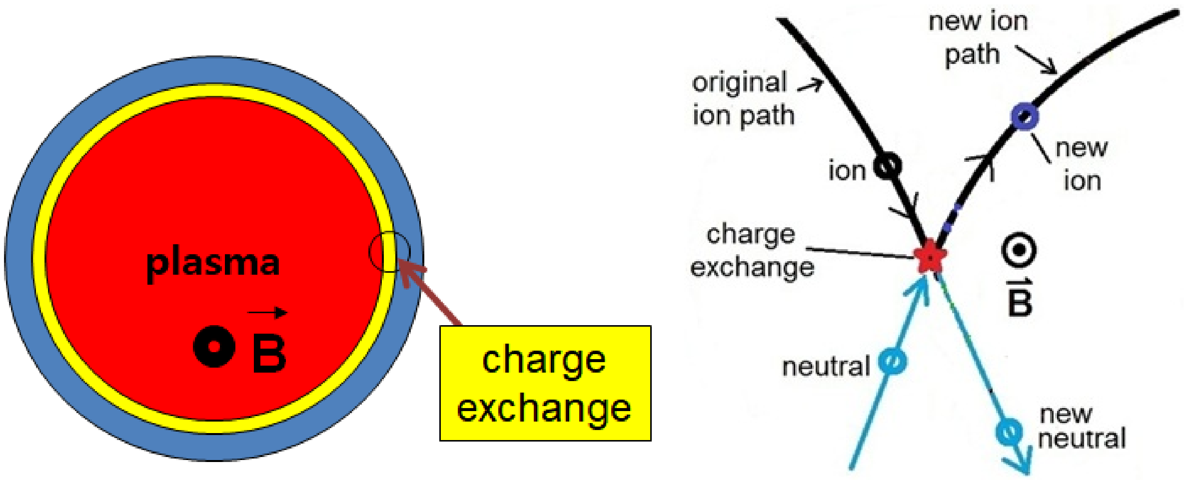

FIG. 1. Diagram of Gyro-Centre Shift mechanism: left is the charge exchange location in the tokamak, right is the indication of shift of ion gyro-centre after the charge exchange reaction.

The charge separation in the plasma is regarded as forbidden by the quasi-neutrality. However, it is found that the charge can be separated when the plasma parameters are in certain conditions such as the Debye length is larger than the radius defined as there is one charge exchange inside its sphere [3]. The GCS analysis explained radial electric field (E_r) formation at the boundary of tokamaks [4], a hundred years old puzzle of reverse motion at the arc discharge cathode spot [5], the origin of Bohm diffusion [6], and the H-mode transition mechanism including the turbulence induced diffusion [7].

3. SIMILARITY OF BLACK AURORA AND ELMS

Recently the GCS analysis explained E-field formation in the earth ionosphere, which includes the equatorial electro-jet (EEJ) at the equator region of ionosphere and the counterpart of EEJ for the polar region of ionosphere which is also known as the aurora [1]. The most interesting part of the ionosphere plasma is the black aurora in which a very strong electric field is measured by the satellites [8]. The black aurora is simply dark region of the aurora. Although the detail mechanism of black aurora formation is unknown, the GCS analysis explained that the strong E-field is result of the plasma-neutral interaction similar to the tokamak boundary. There are two important similarity between the black aurora and the ELM; the first, there is strong electric field in perpendicular direction to the magnetic field, and the second is that these structures break into circular shapes in row with periodic occurrence. A remarkable achievement on KSTAR was the poloidal structure measurement of the ELM by Electron Cyclotron Emission Imaging (ECEI) diagnostics [9]. This similarity is illustrated in Fig.2. Fig.2 (a) is indicating a rare case of the black aurora breaking into a repeated circular pattern in row, and Fig.2 (b) is a diagram how the ExB distortion can make the vortex [10]. Fig.2 (c) is the image of poloidal structure of KSTAR

ELMs measured by ECEI diagnostics. The colour of the circular structure is interpreted as combined effect of electron temperature and density. The region of just inside of separatrix at tokamak edge is the maximum point of E_r well where the positive charge are accumulated by the GCS current. And the dark region of the black aurora is also positive charged by plasma-neutral interaction. The periodic occurrence of vortex street is discussed in the literature for the black aurora [11]. The ELMs in tokamaks and the vortex of black aurora have very different plasma parameters and scales, but have tow common features. The ExB distortion mechanism is suggested for the black aurora, therefore it is important future work to find the role of ExB for the ELM dynamics.

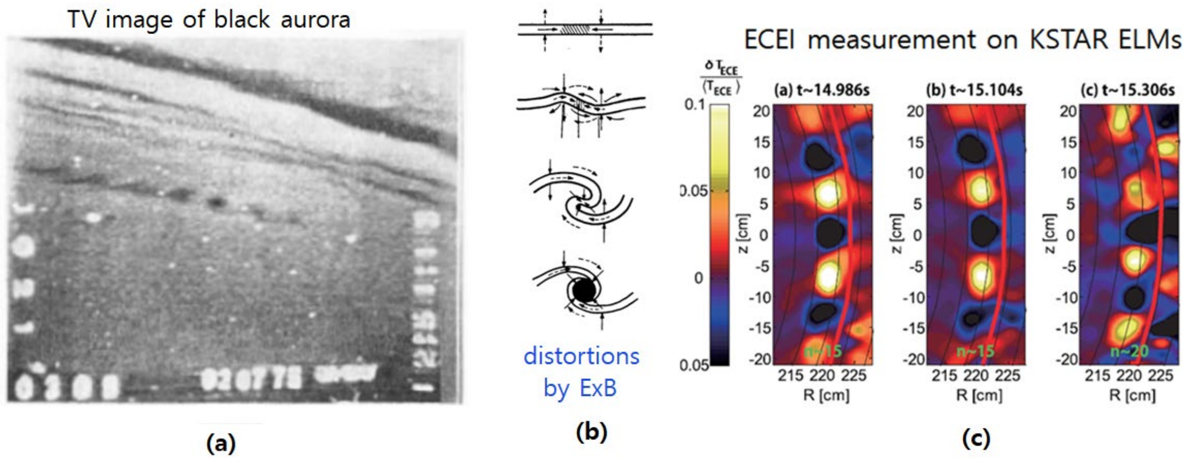

FIG. 2. Circular structure of black aurora and ELMs on KSTAR. (a) The black aurora image captured by camera including vortex [10], (b) vortex formation diagram indicating the distortion by ExB, (c) the circular structure of KSTAR ELMs measured by ECEI (red line is the separatrix) [9].

4. INTRINSIC ROTATION ANALYSIS BY PLASMA-NEUTRAL INTERACTION

The intrinsic rotation of plasma in tokamak is one of the subjects which are not explained thoroughly so far. The plasma rotation is one of the main control parameters for the disruption which is the most important risk of ITER operation. Here we report a new analysis of plasma-neutral momentum exchange, which generates the intrinsic plasma rotation in tokamaks. At early current ramp-up stage, ions are under acceleration in co-current direction and electrons are under acceleration in counter-current direction. These accelerations continue until the momentum loss by the collisions with neutrals. The average distance that charged particle moves before the collision with neutrals is the mean free path λ. The plasma is under acceleration of electric force of qE, here q is a charge and E is the electric field induced by the loop voltage. The energy gain by this force is $qE\lambda$ and it is equal to the kinetic energy. Here the magnitude of ion momentum is different from the electron momentum because the ratio of mass to cross-section is different. However, when the collision frequency is considered for the case where the accelerated velocity is higher than the thermal velocity, the magnitude of momentum change per unit time becomes the same for the ion and electron. This means exactly the same amount of momentum transfer from ions to neutrals in co-current direction occurs from electrons to neutrals in counter-current direction so that they are cancelled out. This momentum change balance is natural since the driving mechanism of momentum change in both directions are the same electric force. However, the momentum change balance can be broken when other mechanisms are involved. There are at least two extra mechanisms that break the balance. The first mechanism is that the thermal velocity is actually higher than electrically accelerated velocity. The second mechanism is the influence from impurity ions. For the case of carbon enriched tokamak, there is a high possibility of C6+ or C3+ impurity contributions. The main ion (D+) contribution to the momentum transfer to the fuelling neutrals (D0) is 100% momentum transfer by charge exchange reaction. But collision of C6+ ion with D0 makes charge exchange resulting C5+ and D+. And C5+ goes back to C6+ by the electron impact ionization. Then these two processes eventually makes an ionization of the main ion, which is not a momentum transfer to the neutral. Other carbon ions such as C3+ can make charge exchange with deuteron neutrals and the result is the same as C6+. If the main ion density is same as C3+ ion with no other impurities, so that the effective ion charge (Zeff) is 2.5, then the electron density is 4 times larger than the main ion density. And the magnitude of momentum transfer from electron to neutral in the counter-current direction is also 4 times of ion to neutral in co-current direction. So the momentum change balance is broken and neutrals are accelerated in the counter-current direction. This momentum transfer acts as a force and it becomes acceleration when divided by the mass of plasma. Finally the toroidal rotation can be calculated by the integration of acceleration during the time constant τ which is related with the plasma confinement time. The detail process of momentum exchange between plasma and neutrals have two folds, first, the unbalanced momentum transfer from plasma to the neutrals generate acceleration for the neutrals, the second part is that this force on neutrals immediately returns back to the plasma. Here the method of momentum transfer is charge exchange so the main ions get the rotation from the neutrals, which is the origin of the intrinsic rotation. In the profile view point, the source of intrinsic rotation take place at the edge of plasma, however the neutrals return this momentum to the ions in the core region. This is very important mechanism of the intrinsic rotation to explain the measured intrinsic rotation profiles where the peak rotation locates in the core. The reason that boundary neutrals can transfer the momentum to the core ions is that the mean free path of the charge exchange reaction is proportional to the plasma density, so the λ for the boundary ions is about 4 m and λ for the core ions is 0.4 m. And another reason is that the neutrals are not confined by the magnetic field, so they can move across the magnetic field. Sometimes even the intrinsic momentum source at the edge is in counter-current direction, but the rotation profile can have co-current rotation at the edge and counter-current rotation in the core. This is possible because ions are basically accelerated in co-current direction by loop voltage, and the neutrals with counter-current momentum which came from the electrons can pass the boundary ions and transfer the momentum to the core ions instead. So the boundary ions are left to keep rotating in the co-current direction. As mentioned above, the key parameter for the intrinsic rotation is the ratio of main ion density to the electron density which is determined by the amount of impurity ions. When the impurity density is higher, the intrinsic rotation can have more in the counter-current direction. One of the important disagreement of the neo-classical simulation from the observation was the collisionality scan of the intrinsic rotation for the main ions and impurity ions [12]. As the collisionality becomes higher the difference between main ions and impurity ions becomes smaller, this aspect is agreed by observation. However the main ion rotation by the neo-classical analysis is higher in co-current direction, while the observation showed the main ion rotation is higher in counter-current direction. This is another supporting evidence that the momentum transfer by the impurity ion is not effective. The ohmic discharge electric field accelerates all ions including impurities in co-current direction, and the electrons accelerated in counter-current direction transfer the momentum to the neutrals. And the neutrals return this momentum to the main ions only, so the main ions have counter-current rotation while the impurity ions remains as co-current rotation. This difference becomes smaller when the Coulomb collisionality is higher because of the momentum exchange between main ions and impurity ions. The KSTAR ohmic discharge experiment showed typical trend of intrinsic rotation on more than 400 plasma shots, which is peak intrinsic rotation in counter-current direction at the current ramp-up stage and slowing down toward the co-current direction [13]. This typical intrinsic rotation trend is indicated in Fig. 3, and well agreed the calculation value by the analysis based on the plasma-neutral interaction.

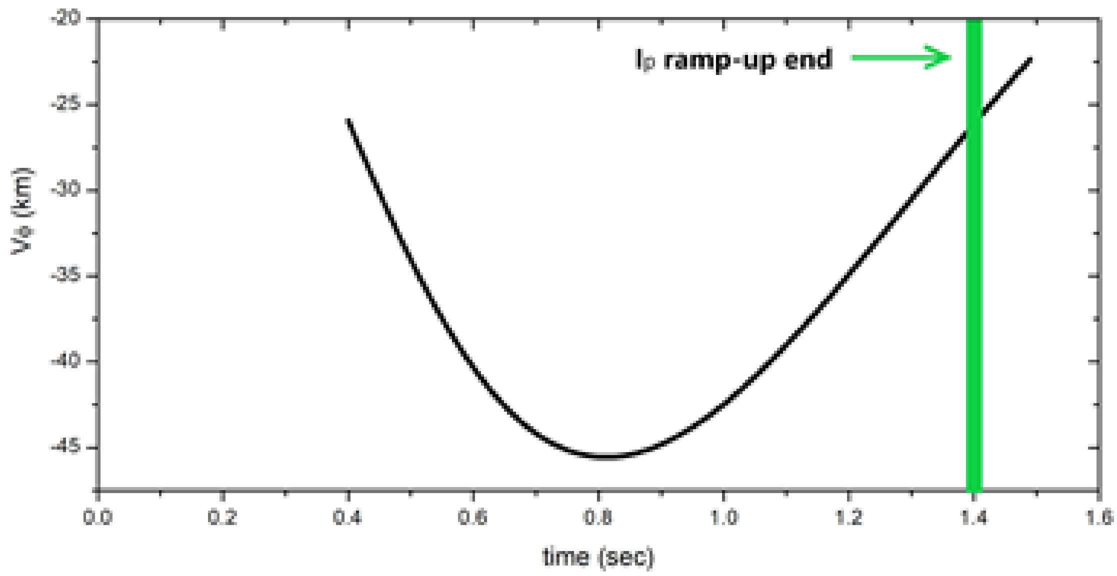

FIG.3 Toroidal velocity induced by the plasma-neutral momentum exchange for the typical KSTAR ohmic discharge.

.

5. CONCLUSIONS

The importance of plasma-neutral interaction has been underestimated for long time. This research strategy should be corrected since the major tasks of fusion energy development are dependent on this aspect of plasma physics. The reason for the importance of momentum exchange by neutrals in the perpendicular direction to the magnetic field is that the all the charged particles are following the ExB drift induced by the Lorentz force while the neutrals are not. So the Coulomb collisions don't make a difference like as bumping each other of passengers in a train doesn't make any acceleration or deceleration of the train. The only collision to make the train accelerated is the collision with something out of the train. The collision of charged particle with neutrals in the E-field and B-field can be an analogy of the collision from outside of the train. The plasma-neutral interaction in the parallel direction to the magnetic field is also important in the case of intrinsic rotation, where the rotation force qE is originated from the toroidal electric field. Therefore, if there is no neutrals, the total amount of force acting on ions and electrons is opposite each other with same magnitude and the force would be cancelled. This is how the Coulomb collisions are not effective for the generation of intrinsic rotation. It is analyzed that the intrinsic rotation is induced by the unbalanced momentum exchange between the ion-neutral and the electron-neutral. The calculated value of intrinsic rotation by this analysis is quantitatively agreed with the experimental measurement for the first time. The GCS analysis based on the plasma-neutral interaction can explain the E_r formation of tokamak boundary and the critical parameter for the L/H transition, which is the second important risk of the ITER operation. The similarity of black aurora and ELMs can provide the solution of ELM formation mechanism from which a mitigation method can be developed, which is related with the third important risk of ITER operation. Finally the understanding of the plasma rotation is directly related with how we avoid the damage by the disruptions, which is the most important risk of ITER operation. For the realization of the commercial nuclear fusion energy production, it is necessary to include the plasma-neutral interaction in the fusion plasma analysis. And the development of the diagnostics system that can measure the neutral density profile is an important future task.

ACKNOWLEDGEMENTS

This research was supported by R&D Program of KSTAR Experimental Collaboration and Fusion Plasma Research through the Korea Institute of Fusion Energy (KFE) funded by the Government funds.

REFERENCES

[1] Lee, K. C., *Phys. Plasmas* **24** 112505 (2017).
[2] Shaing, K. C., Ida, K., Sabbagh, S.A. Nucl. Fusion 55, 125001 (2015).
[3] Lee, K. C., "Violation of Quasi-neutrality for Ion-neutral Charge-exchange Reactions in Magnetized plasmas", J. Korean Phys. Soc. 63 , pp1944-1949, Nov. (2013).
[4] Lee, K. C., Phys. Plasmas 13 062505 (2006)
[5] Lee, K. C. Gyrocenter Shift of Low-Temperature Plasmas and the Retrograde Motion of Cathode Spots in Arc Discharges. Phys. Rev. Lett., 99, 065003 (2007).
[6] Lee, K. C. Analysis of Bohm Diffusions Based on the Ion-Neutral Collisions. *IEEE Trans. Plasma Sci.* **43**, 494-500 (2015)
[7] Lee, K. C. Analysis of turbulence diffusion and H-mode transition in conjunction with gyrocentre shift at the boundary of fusion devices. *Plasma Phys. Control. Fusion,* **51**, 065023 (2009).
[8] Marklund, G. T. Auroral phenomena related to intense electric fields observed by the Freja satellite. *Plasma Phys. Control. Fusion,* **39**, A195-A226 (1997).
[9] Jaehyun Lee, Gunsu Yun, *et al*, Phys. Rev. Lett., **117**, 075001 (2016)
[10] T.J. Hallinan, and T. N. Davis, Planet. Space Sci., 18, 1735-1744 (1970)
[11] Shukla, P. K.; Birk, G. T.; Bingham, R. Geophysical Research Letters, Volume 22, Issue 6, p. 671-674 (1995)
[12] Grierson, B. A. Burrell, K.H., Solomon, W.M., Budny, R.V., and Candy, J., Nucl. Fusion 53 063010 (2013).
[13] S. G. Lee, *Phys. Plasmas* **27** 064503 (2020).