Plasma-neutral momentum exchange and its applications to edge localized mode and toroidal rotation on tokamaks

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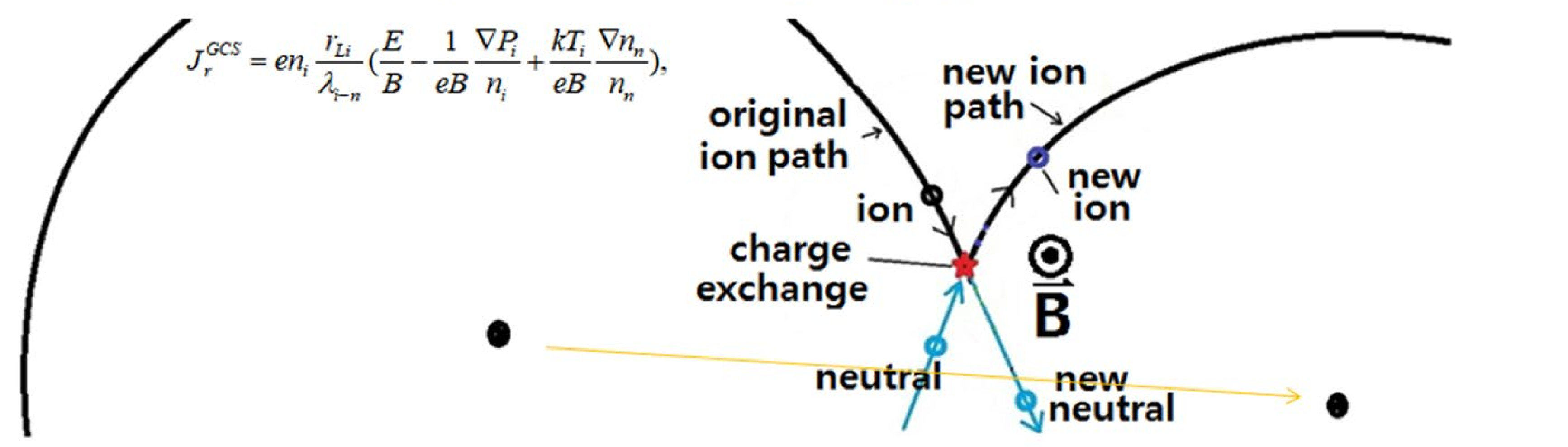
ABSTRACT

- 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.

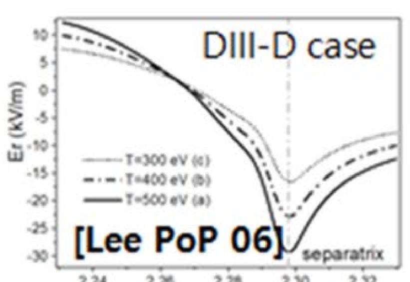
BACKGROUND: E-Field formation by plasma-neutral collision

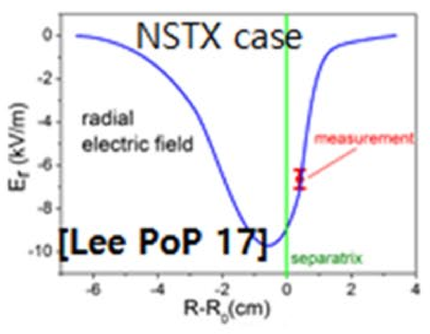
introduction to Gyro-Center Shift (GCS) by ion-neutral collisions

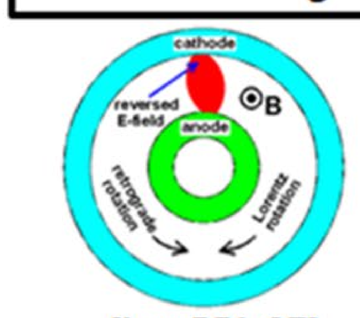
$$J_r^{GCS} = en_i \frac{r_{Li}}{\lambda_{i-n}}\left(\frac{E}{B} - \frac{1}{eB}\frac{\nabla P_i}{n_i} + \frac{kT_i}{eB}\frac{\nabla n_n}{n_n}\right),$$



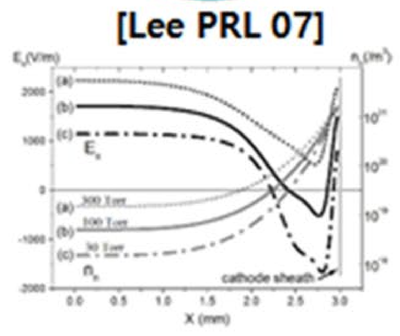
Er well formation at tokamak edge	reverse motion of cathode spot in arc discharge	origin of Bohm diffusions	vertical E-field of equatorial electro-jet (EEJ)



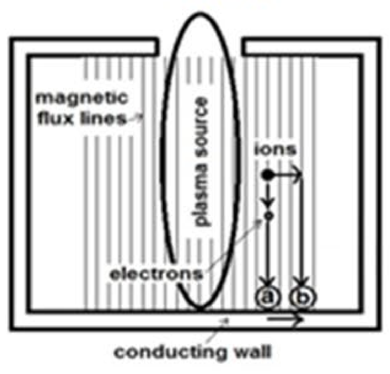




[Lee PRL 07]

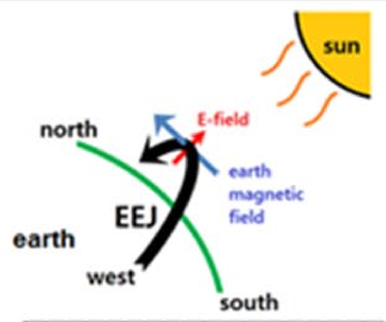


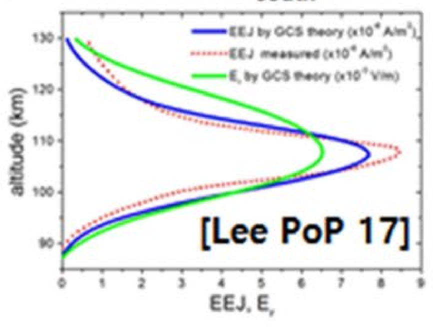
$$D_B = \frac{1}{16}\frac{kT_e}{eB}$$



$$D = \frac{2r_L}{\lambda_{cx}}\frac{kT_i}{eB}$$

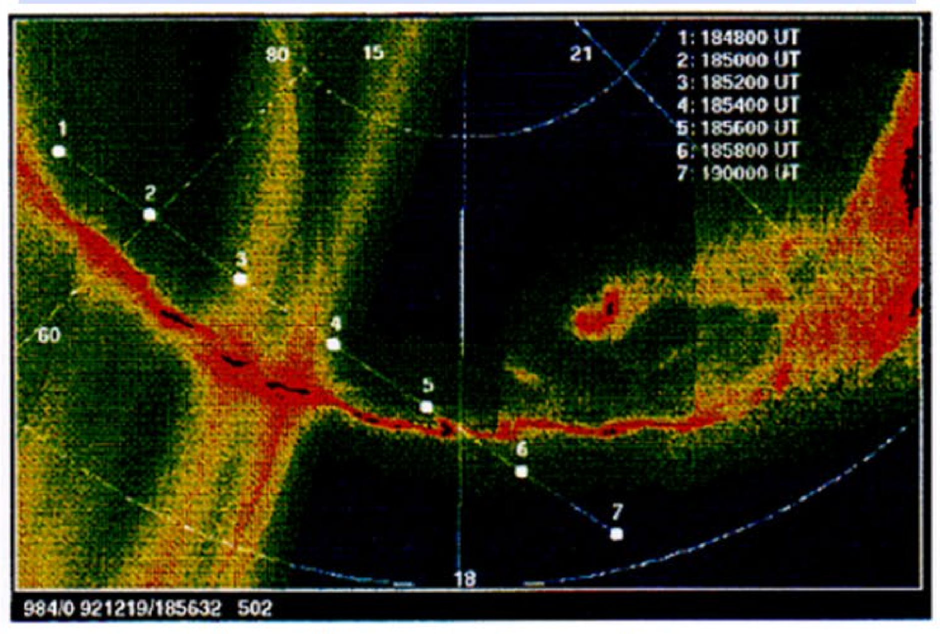
[Lee IEEE 15]





E-Field across black aurora

Strong E-field is found across the black aurora



Swedish satellite Freja observed strong cross E-field on black aurora [Marklund, PPCF 1997]

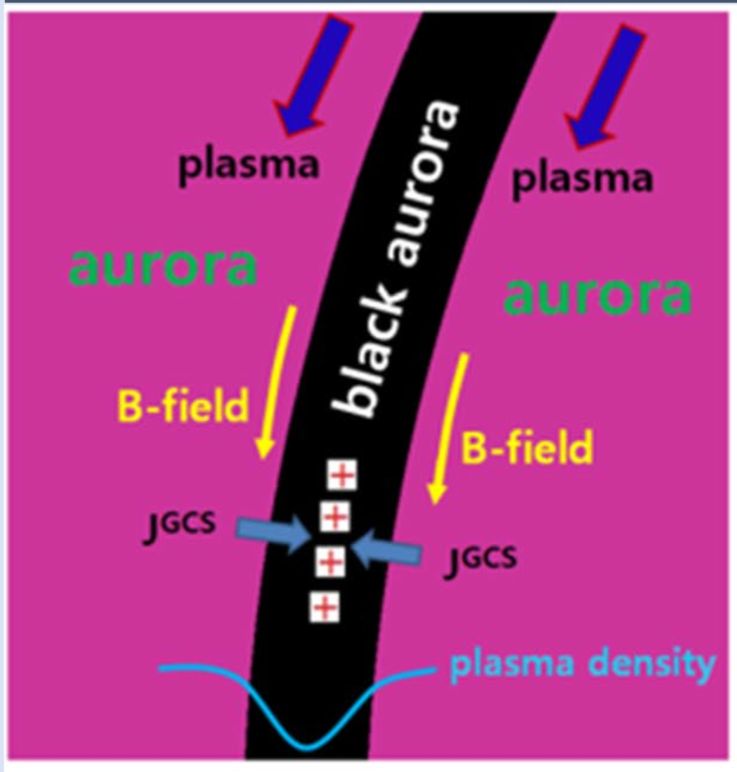
CONCLUSION

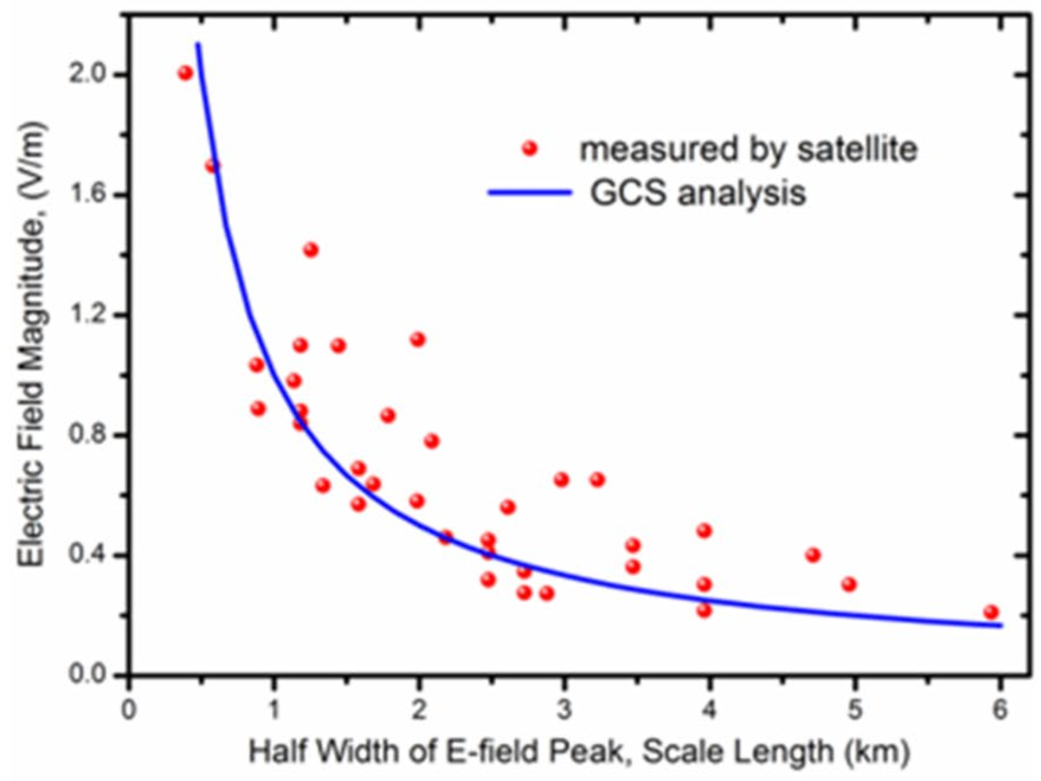
1. Plasma-neutral interface with B-field ➡ E-field formation (regardless of scale : arc discharge, tokamak, ionosphere)

2. Two common features of black aurora and ELM
   - strong E-field cross the magnetic field
   - interface breaks into circular structure

3. Intrinsic rotation of fusion plasma is analyzed by plasma-neutral interaction.
   - unbalanced momentum transfer between ion ➡ neutral & electron ➡ neutral
   - ratio of main ion to the impurity ion is key parameter

Black aurora analysis & measurement





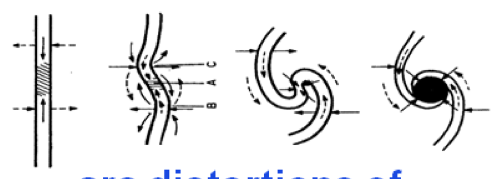
$$\frac{qn_i}{\omega_c\tau}\left(\frac{E}{B} - \frac{\nabla P_i}{qBn_i} + \frac{kT_i}{qB}\frac{\nabla n_n}{n_n}\right) \approx 0 \qquad E \approx kT_i/qL_n$$

Agreements;

1. **polarity : always positive in black aurora**
2. **magnitude : 1keV ions with 1 km scale length 1 V/m**
3. **dependence on scale length: narrower generates stronger E-field**

First common feature of black aurora and tokamak edge : strong E-field
Second : breaking into circular structure

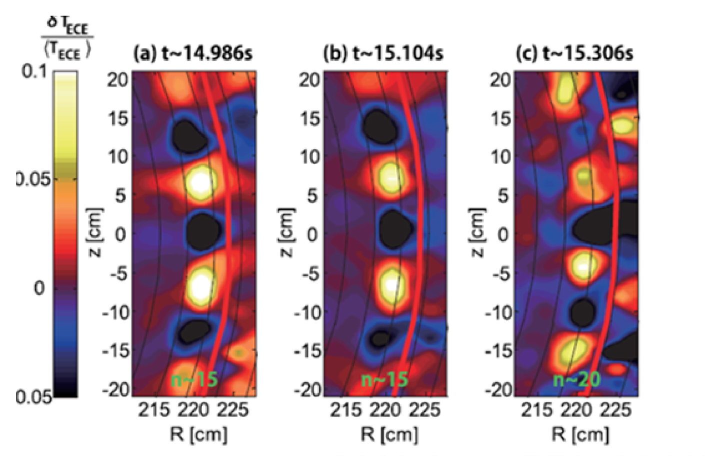
TV image of black aurora



arc distortions of black aurora by ExB

[Hallinan and Davis, Planet. Space Sci. 1970]

ECEI measurement on KSTAR ELMs



[J.H. Lee, PRL 2016]

Future works: ELMs take place only at H-mode
What is the role of strong E_r for the ELM triggering?

Intrinsic rotation analysis by plasma-neutral interaction

► **ion-electron momentum exchange by Coulomb collisions is universally cancelled**

electrons are under eE for distance of $\lambda = 1/\sigma_{ei}n_i$

$$\frac{1}{2}mv_e^2 = eE\lambda \Rightarrow mv_e \qquad \frac{1}{2}M_Z v_i^2 = ZeE\frac{1}{\sigma_{ie}n_e}\frac{M_Z}{m} \Rightarrow mv_i \quad \times m/M_Z$$

e-i collision frequency : $\nu = \sigma_{ei}v_{Te}n_i$ i-e collision frequency : $\nu = \sigma_{ie}v_{Te}n_e$

$$\sum_Z \left(-2n_{ez}\sqrt{eEkT_e\sigma_{ei}n_z} + 2n_z\sqrt{ZeEkT_e\sigma_{ie}n_{ez}}\right) = 0 \qquad (n_{ez} = Zn_z \text{ and } \textstyle\sum_Z n_{ez} = n_e)$$

► **momentum exchange by collisions with neutrals**

electron-neutral

$$\frac{1}{2}mv_e^2 = \frac{eE}{\sigma_{en}n_n}$$

$$mv_e = -\sqrt{\frac{2eEm}{\sigma_{en}n_n}}.$$

ion-neutral (charge exchange)

$$D^+ \to D^0 \to D^0 + D^+$$

$$C^{6+} \to D^0 \to C^{5+} + D^+$$
$$e \to C^{5+} \to C^{6+} + 2e$$

impurity ion- neutral reaction is not effective

neutrals quickly return the momentum to ions by C.X. without staying in the plasma

$$\sigma_{en} = 3\times10^{-19}/\sqrt{T_e} \qquad \sigma_{in} = 2.7\times10^{-19}\times e^{-T_i/3430}$$

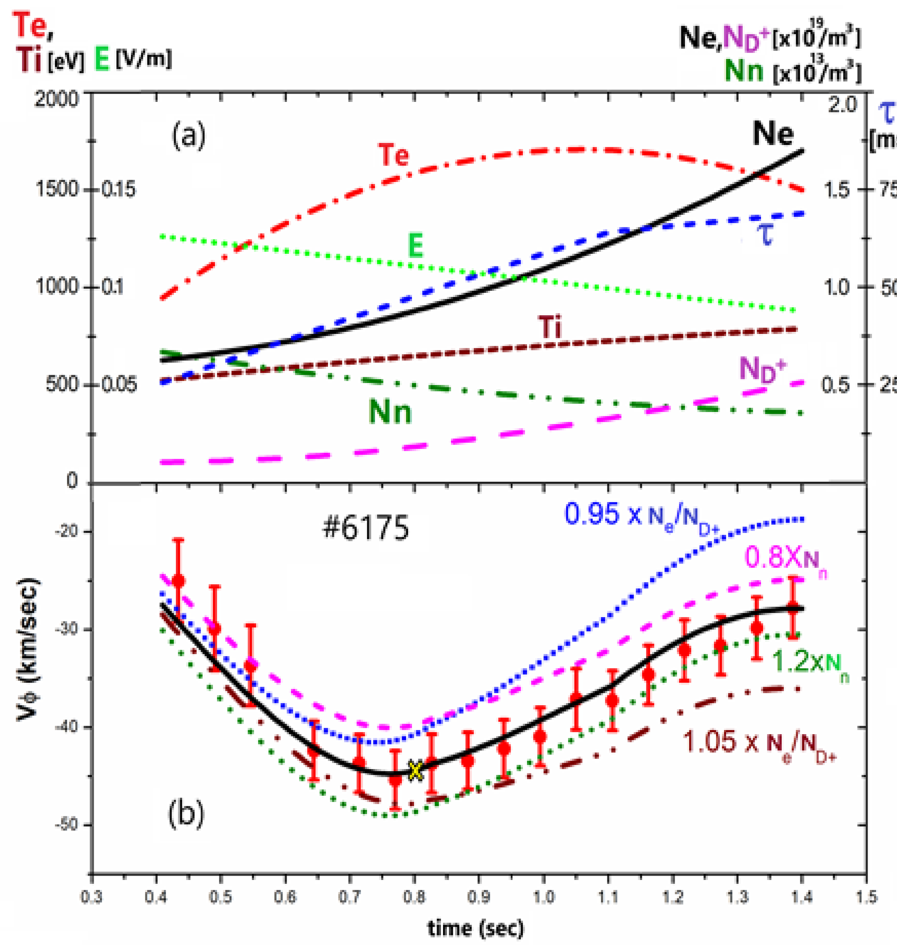
$$\dot{P}_e = -2n_e\sqrt{eEkT_e\sigma_{en}n_n} + \dot{P}_{D+} = 2n_{D+}\sqrt{eEkT_i\sigma_{in}n_n}$$

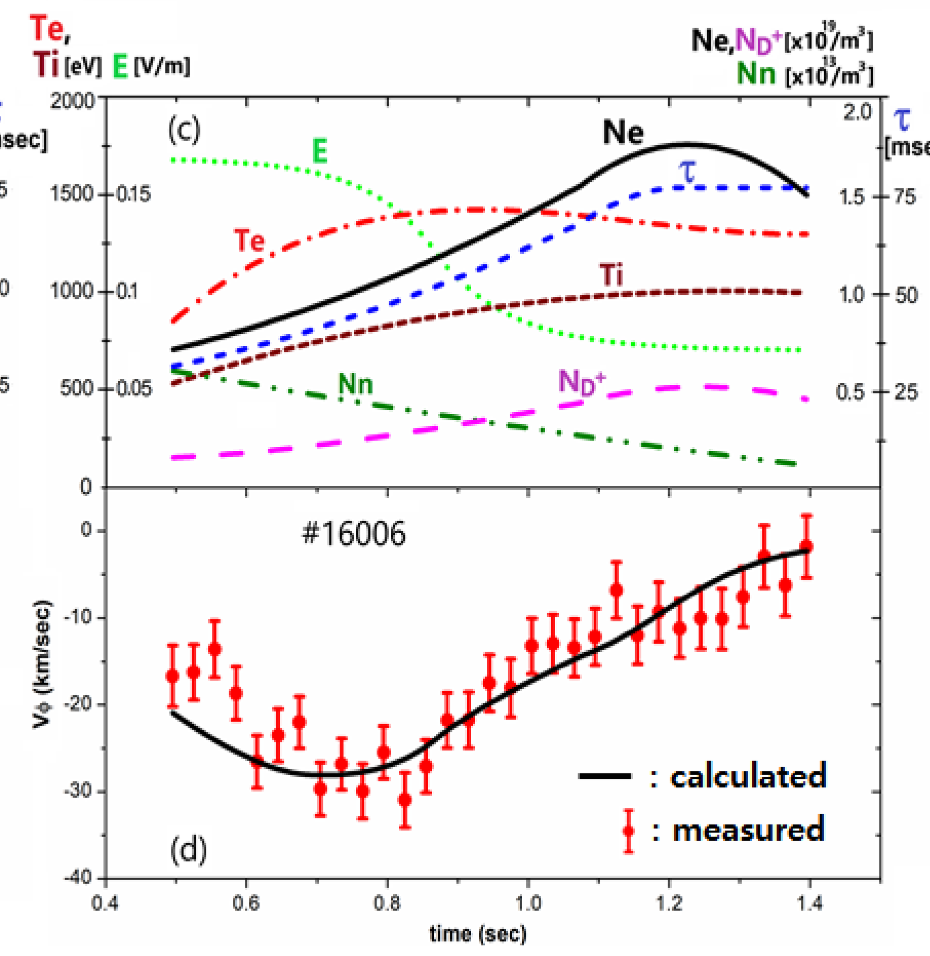
$$V_\phi = 2\tau\sqrt{eEn_n}\left(n_{D+}\sqrt{kT_i\sigma_{in}} - n_e\sqrt{kT_e\sigma_{en}}\right)/M_p,$$

(τ is the acceleration time and M_p is the plasma mass)

V_ϕ is non-zero unless n_{D+}/n_e , T_i/T_e , σ_{in}/σ_{en} are in symmetry

comparison to KSTAR ohmic discharge rotation measurements





First theoretical analysis quantitatively agrees experiment on intrinsic rotation

ACKNOWLEDGEMENTS / REFERENCES

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- [1] K. C. Lee, *Phys. Plasmas* **24** 112505 (2017)