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

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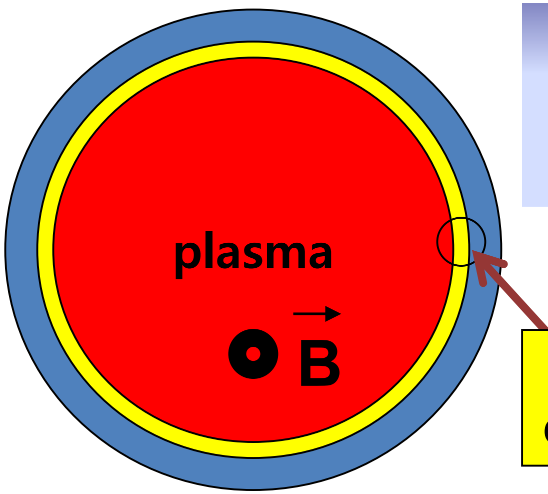
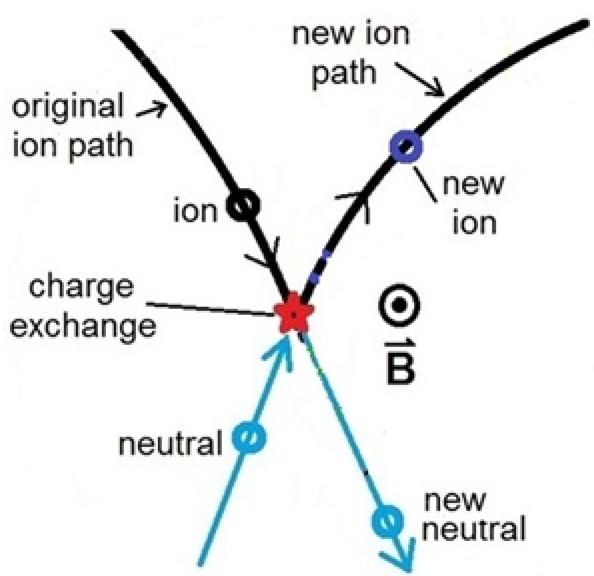
Contents

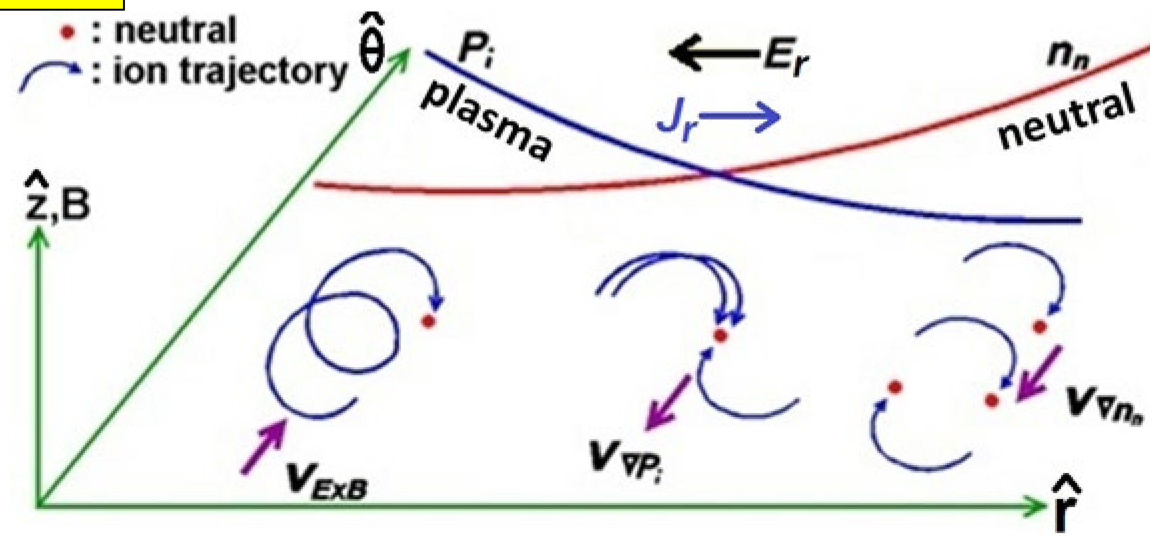
time dependent problem!
(conventional force is not balanced)



charge exchange

$$\vec{J} \times \vec{B} = n_i \nu_{i-n} m_i \upsilon^*$$





$$\nu_{i-n} = \sigma_{i-n} \upsilon_i n_n$$

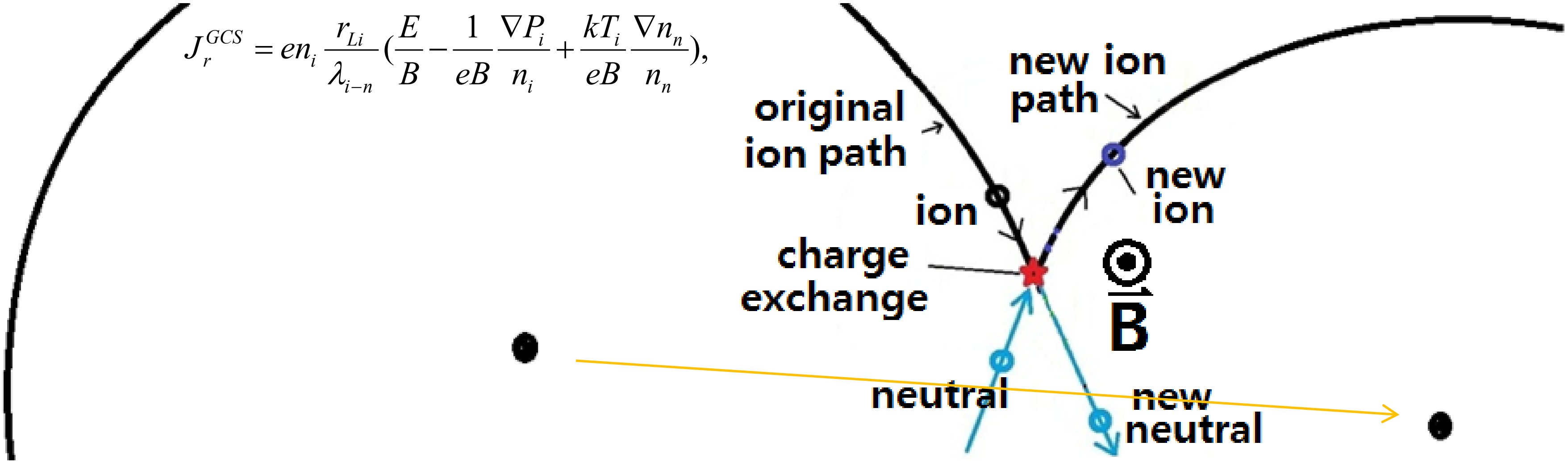
$$J_r^{GCS} = q n_i \frac{\nu_{i-n}}{\omega_{ci}} \underbrace{\left[\frac{E}{B} - \frac{\nabla P_i}{q B n_i} + \frac{k T_i \nabla n_n}{q B n_n} \right]}_{\upsilon^*}$$

radial current by ion-neutral collision

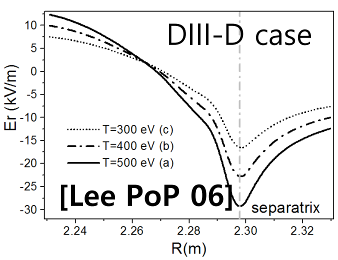
3

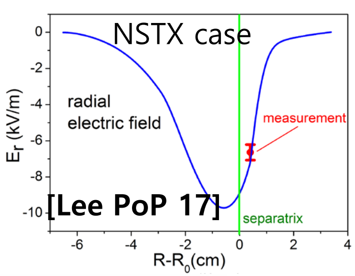
introduction to Gyro-Center Shift (GCS) by ion-neutral collisions

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

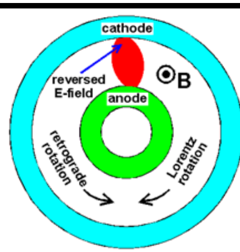


Er well formation at tokamak edge

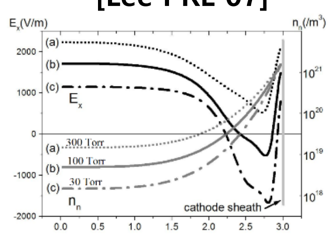




reverse motion of cathode spot in arc discharge

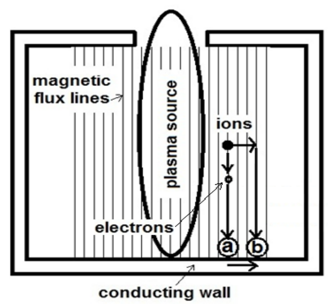


[Lee PRL 07]



origin of Bohm diffusions

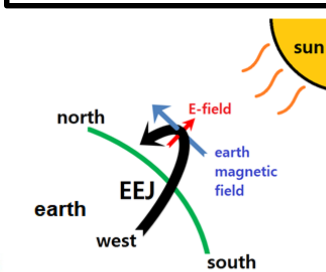
$$D_B = \frac{1}{16}\frac{kT_e}{eB}$$

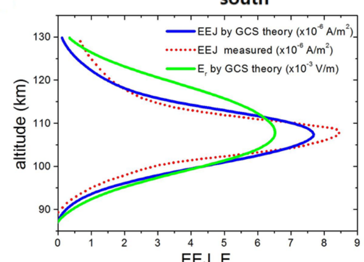


$$D = \frac{2r_L}{\lambda_{cx}}\frac{kT_i}{eB}$$

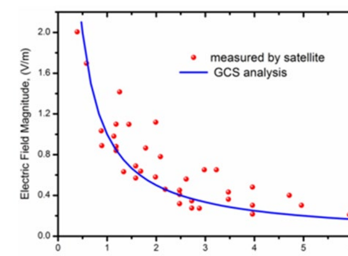
[Lee IEEE 15]

vertical E-field of equatorial electro -jet (EEJ)



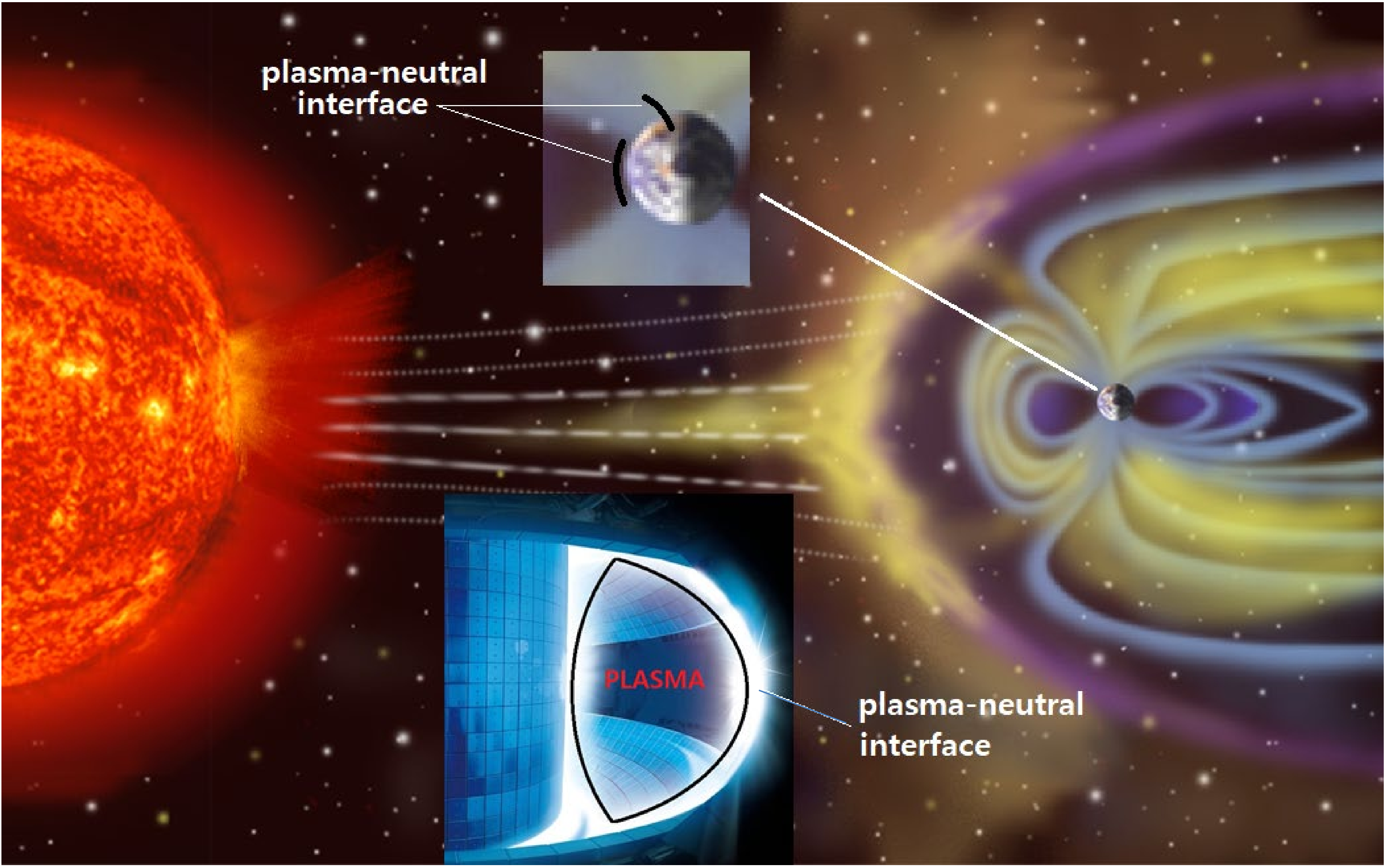


E-field formation of black aurora



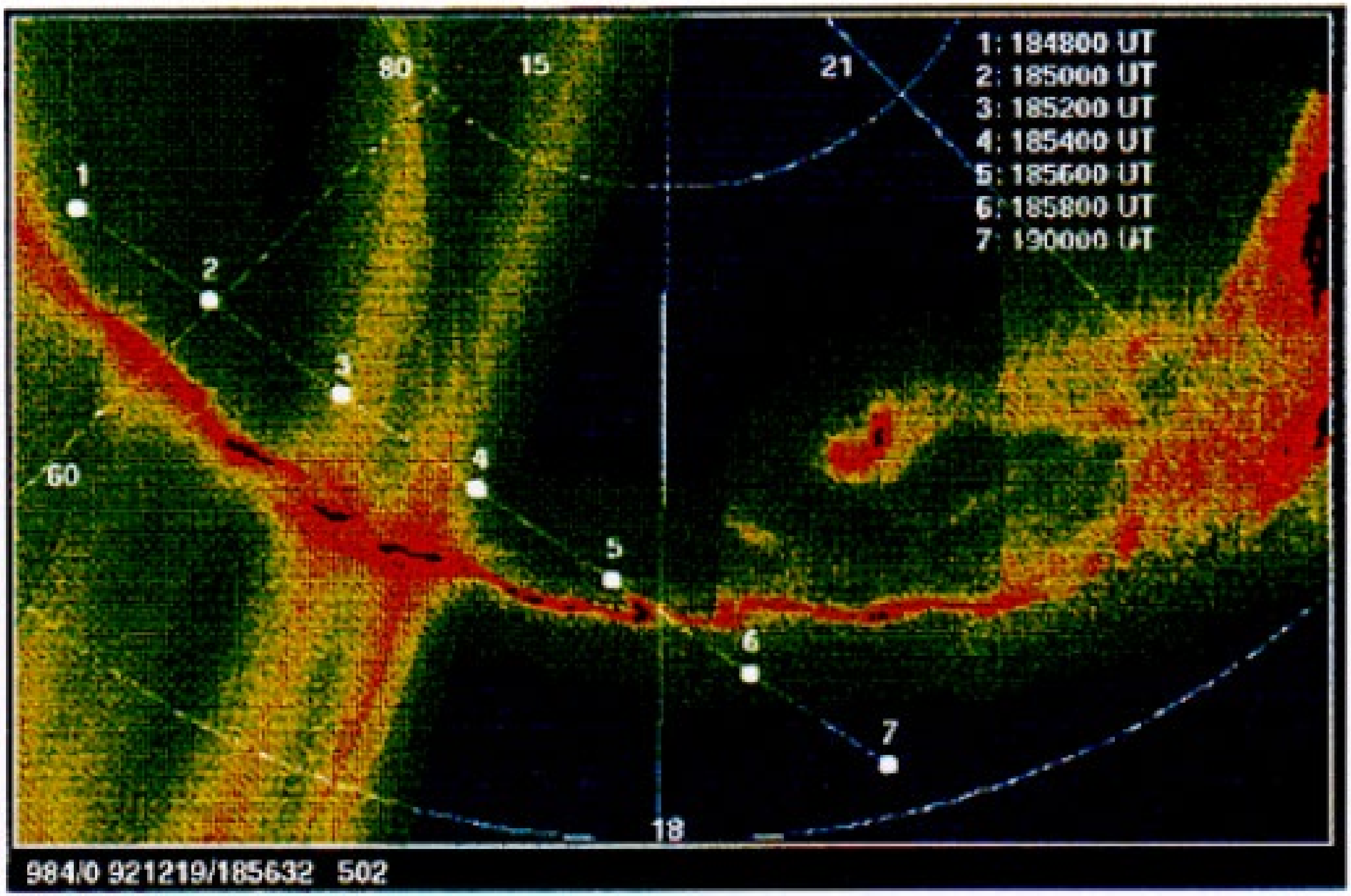
[Lee PoP 17]

Introduction : earth ionosphere vs. tokamak

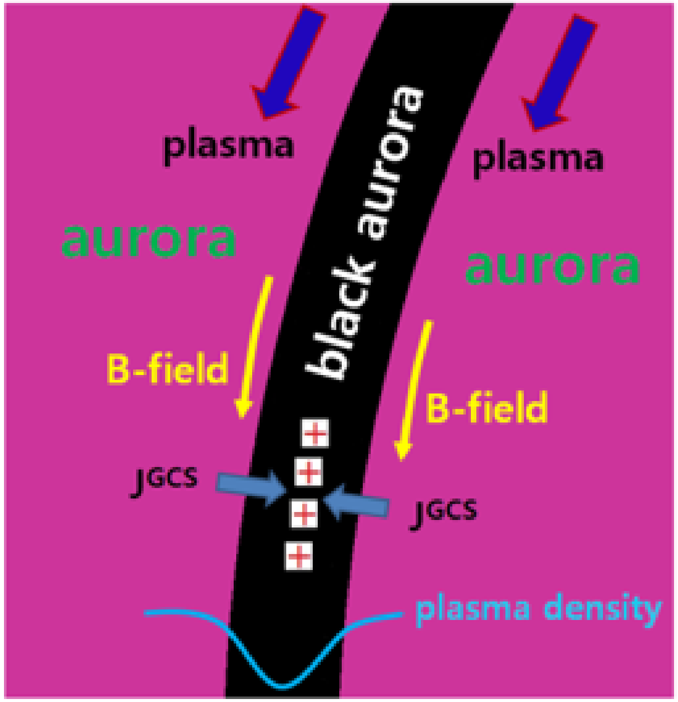


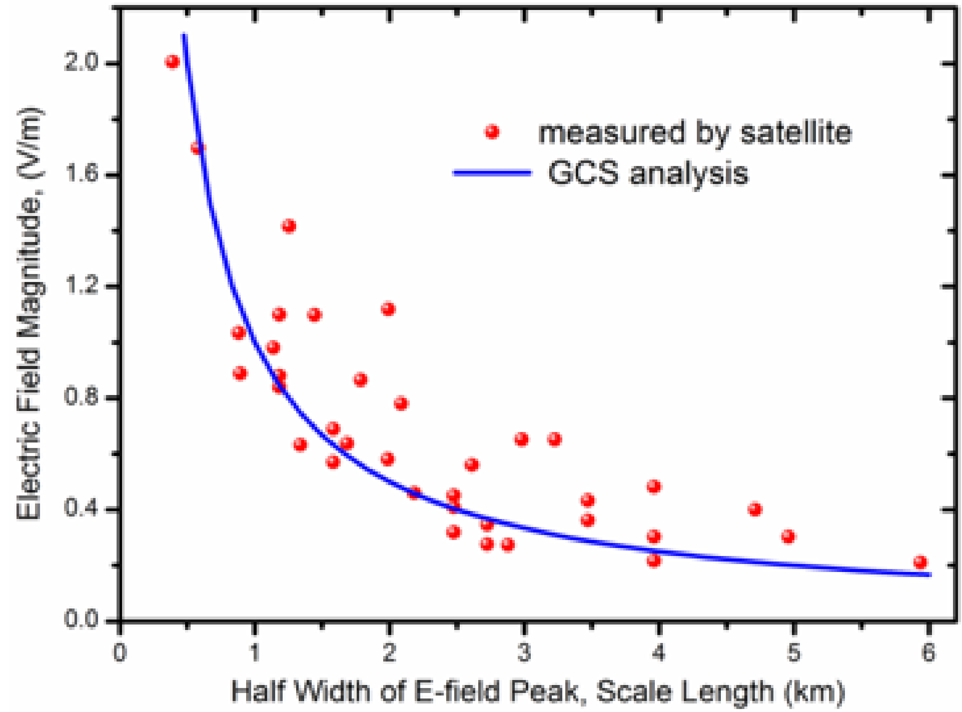

black aurora simply represent
the absence of aurora

Strong E-field is found across the black aurora



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





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

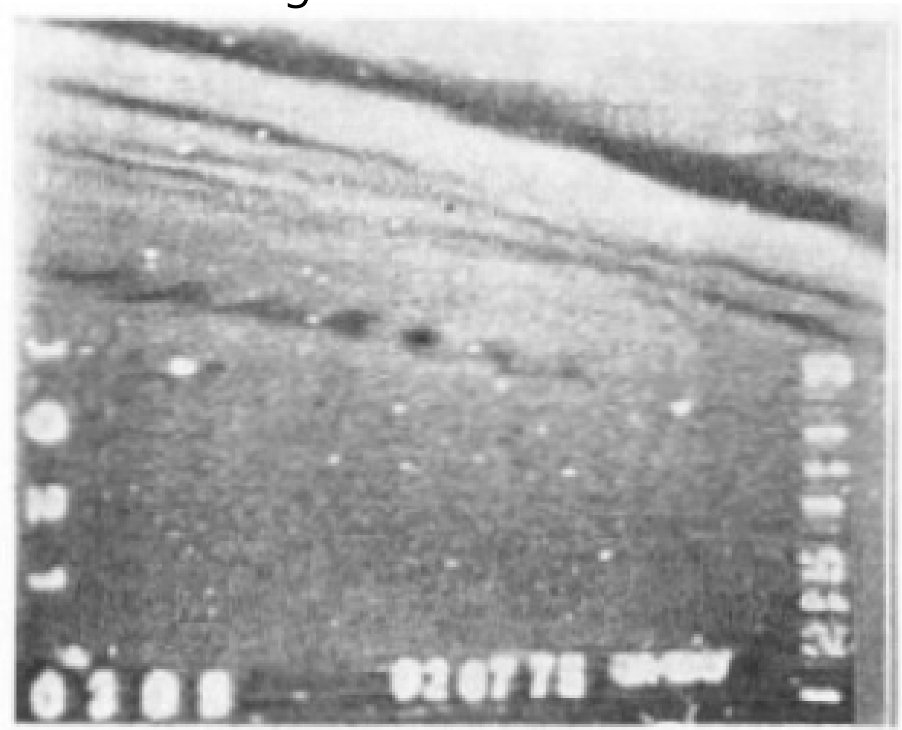
$$E \approx kT_i / qL_n$$

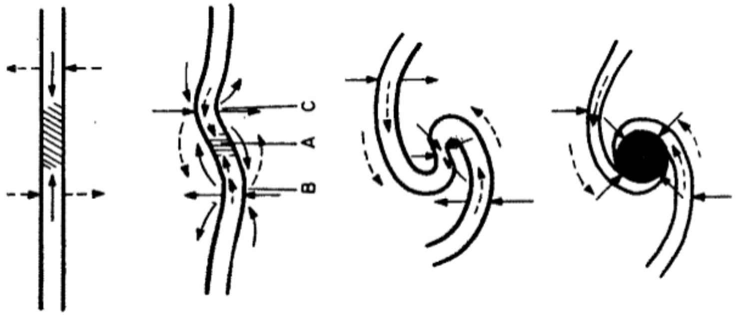
Agreements;

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

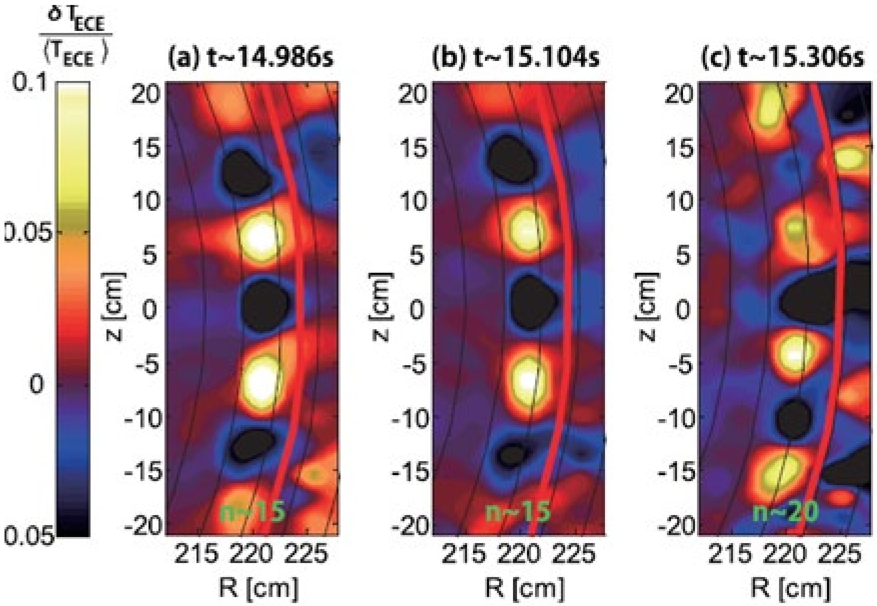




arc distortions of black aurora by ExB

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

ECEI measurement on KSTAR ELMs



[J.H. Lee, PRL 2016]

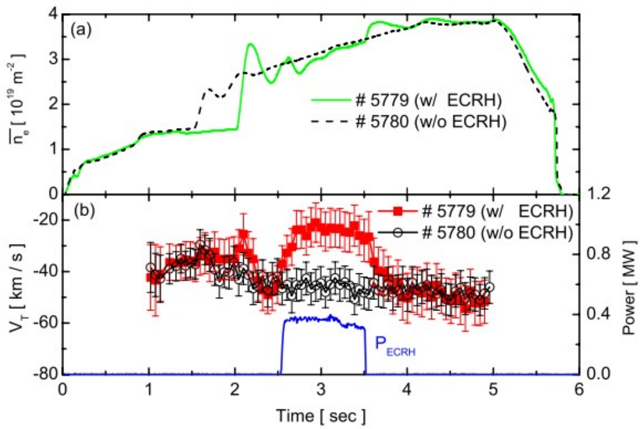
Future works:
ELMs take place only at H-mode
What is the role of strong E_r
for the ELM triggering?

intrinsic rotation by electron-neutral & ion-neutral collisions

PRL **109**, 195003 (2012) PHYSICAL REVIEW LETTERS week ending 9 NOVEMBER 2012

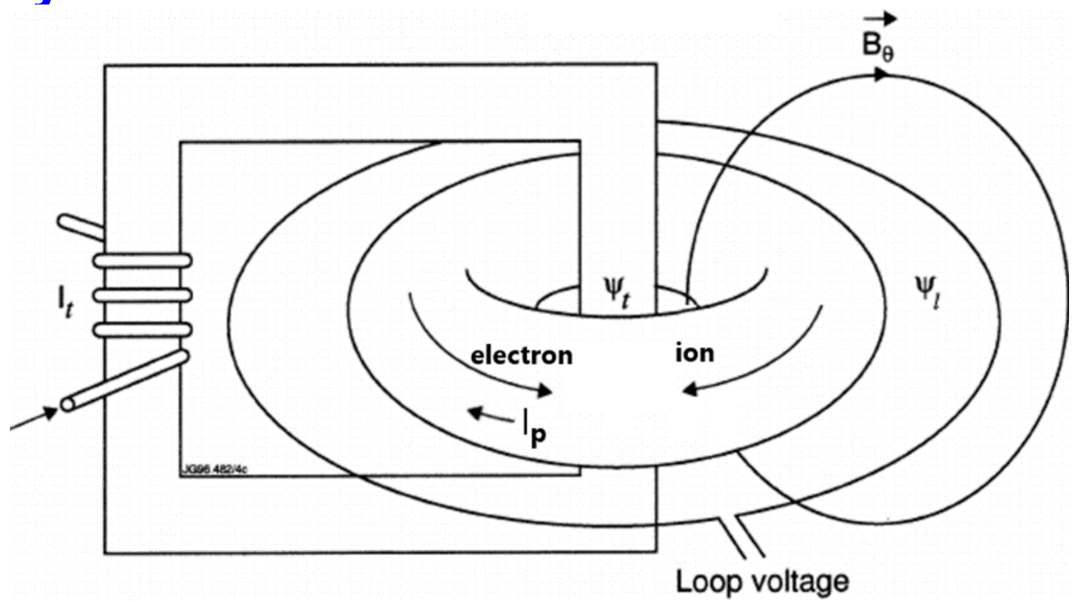
Effects of Electron-Cyclotron-Resonance-Heating-Induced Internal Kink Mode on the Toroidal Rotation in the KSTAR Tokamak

J. Seol,[1] S. G. Lee,[1] B. H. Park,[1] H. H. Lee,[1] L. Terzolo,[1] K. C. Shaing,[2,3] K. I. You,[1] G. S. Yun,[4] C. C. Kim,[5] K. D. Lee,[1] W. H. Ko,[1] J. G. Kwak,[1] W. C. Kim,[1] Y. K. Oh,[1] J. Y. Kim,[1] S. S. Kim,[1] and K. Ida[6]



$v_{\parallel}$ vs. $v_{\perp}$

► ion-electron momentum exchange by Coulomb collisions



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

$$\frac{1}{2} m v_e^2 = eE\lambda \Rightarrow m v_e$$

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

$$\frac{1}{2} M_Z v_i^2 = ZeE \frac{1}{\sigma_{ie} n_e} \frac{M_Z}{m} \Rightarrow m v_i$$

$\times m/M_Z$

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

$$\sum_Z \left(-2n_{ez}\sqrt{eEkT_e\sigma_{ei}n_z} + 2n_z\sqrt{ZeEkT_e\sigma_{ie}n_{ez}}\right) = 0$$

$(n_{ez} = Zn_z$ and $\sum_Z n_{ez} = n_e)$

► momentum exchange by collisions with neutrals

electron-neutral

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

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

$$\dot{P}_e = -2n_e\sqrt{eEkT_e\sigma_{en}n_n}$$

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

$$\dot{P}_{D+} = 2n_{D+}\sqrt{eEkT_i\sigma_{in}n_n}$$

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

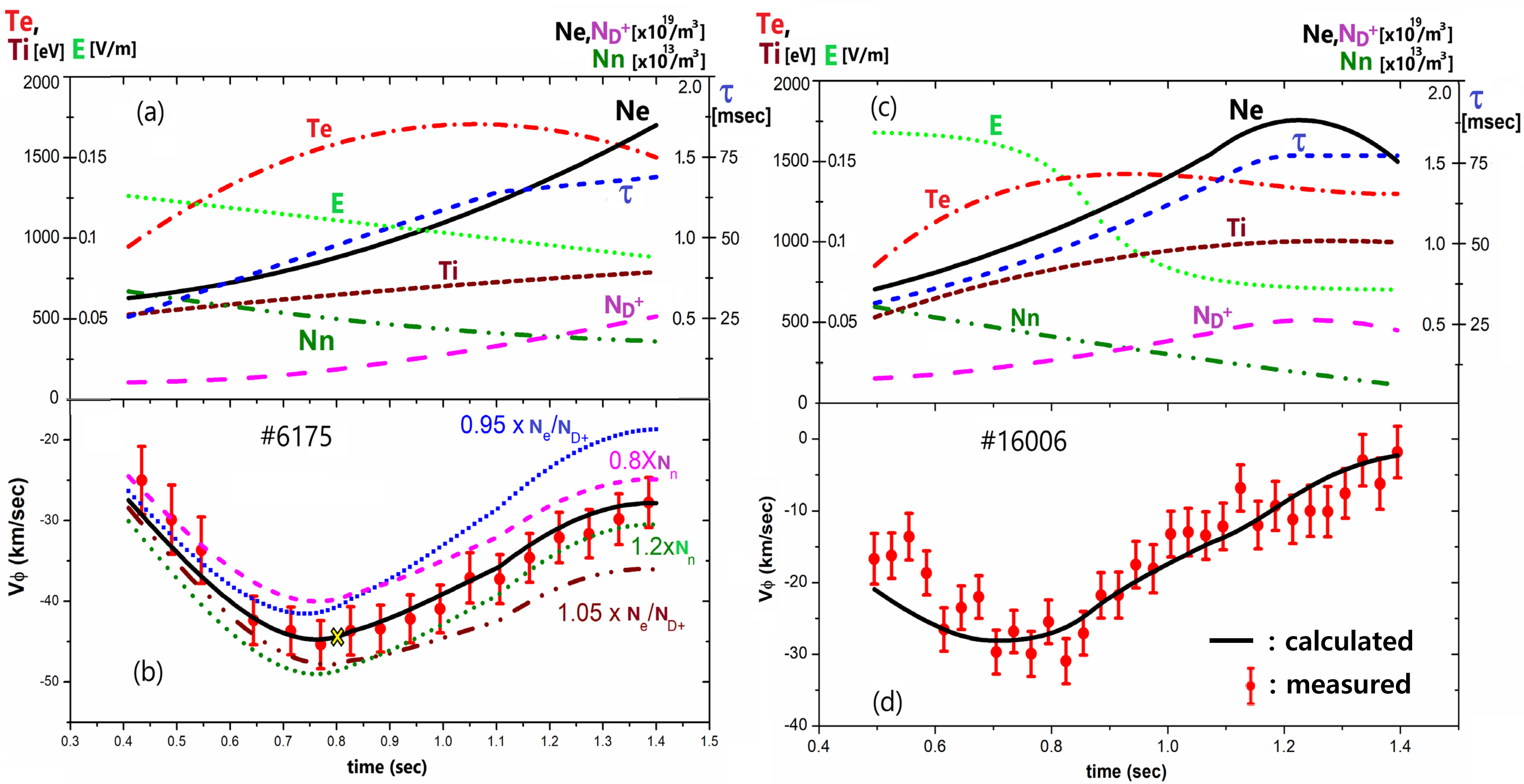
$$V_\phi = 2\tau\sqrt{eEn_n}(\,n_{D+}\sqrt{kT_i\sigma_{in}} - n_e\sqrt{kT_e\sigma_{en}})/M_p,$$

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

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

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



- Calculation matched well for two shots (with different time trend)
- First theoretical analysis quantitatively agrees experiment

Conclusions

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