# Collisionless Plasma Transport Mechanisms in Open Stochastic Magnetic Field Lines Associated with Thermal Quench

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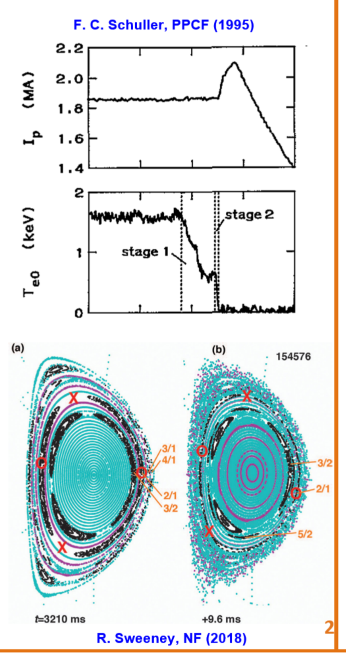
## Thermal quench transport is critical issue in tokamak disruption problem

- **The plasma disruption is a major challenge of tokamak fusion plasma**
  - Thermal Quench (TQ) and Current Quench (CQ)
  - Rapid release of thermal and magnetic energy can damage to PFCs
- **Causes of TQ depend on causes of disruption**
  - Intentional plasma shutdown for machine protection
    - Impurity pellet injection or massive gas puffing
    - Radiative cooling of bulk thermal plasma
  - Disruptive MHD instabilities
    - Vertical displacement events
    - Locked Mode → magnetic islands grow & overlap → Break magnetic surface → stochastic magnetic fields
  - Duration of TQ ~ a few milliseconds → huge heat load to PFCs

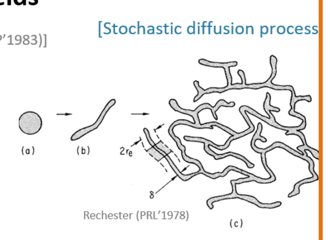
➡ What are ***plasma transport mechanisms*** including ***kinetic electron effects*** in the presence of ***open stochastic magnetic field lines***?



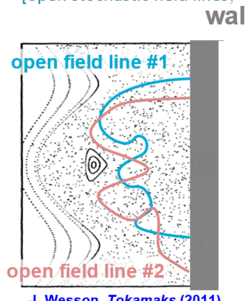

## This study focus on the "3-D kinetic effects" of the plasma transport in "open" stochastic field lines

- **Previous theoretical studies on plasma transport in stochastic magnetic fields**
  - Parallel transport + collisional cross-field decorrelation [Rechester& Rosenbluth (PRL'1978), Krommes (JPP'1983)]
  - $\nabla B$ and curvature drift effects due to the toroidal geometry [Mynick (1979, 1980)]
  - Ambipolar electric fields for quasi-neutrality [Harvey (PRL'1980)]

➡ Stochastic fields are typically characterized by 0-D or 1-D diffusion coefficient

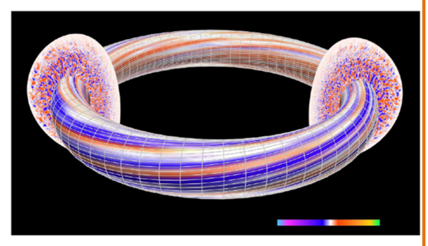



- **Key effects essential for understanding the Thermal Quench physics**
  - ***Open*** stochastic magnetic field lines connecting to the wall
    → significant ***particle loss*** to the wall
  - 3-D topology of the stochastic magnetic field lines
  - 3-D ambipolar electric fields for quasi-neutrality of the plasma
    → dynamics of ***trapped electrons*** (magnetic mirror + electric potential well)
    → cross-field decorrelation by $\boldsymbol{E_\perp \times B}$ transport and mixing effects




## New 3-D kinetic capabilities have been developed to study collisionless mechanisms of the plasma transport in open stochastic fields

- GTS (Gyrokinetic Tokamak Simulation)
  - PPPL-based code led by W. Wang
  - A global gyrokinetic particle simulation code to study **micro turbulence physics** of the fusion plasma in tokamaks
  - New 3-D kinetic capabilities have been developed to study the plasma transport in the stochastic open magnetic field lines
  - Focus on electrostatic plasma responses in the collisionless limit (high temperature plasma & short connection length)



- Step-by-Step approach
  1. High-resolution vacuum field analysis → 3-D magnetic topology
  2. Test particle simulation → Magnetically passing and trapped electrons
  3. Ambipolar $E_\parallel$ effect → Quasi-neutrality & additional electron trapping by ambipolar potential
  4. $E_\perp \times B$ effect → Key cross-field decorrelation mechanism

## Prescribed $\delta B$ applied on "Cyclone base case" Equilibrium

- **Equilibrium magnetic configuration**
  - "Cyclone base case"
- **Circular shape wall boundary at $\sqrt{\psi_t} = 0.9$**
  - Absorbing particle wall
  - Grounded conductor ($\Phi = 0$ at the wall)
- **Static magnetic perturbations with multiple harmonics**
  (TQ time scale) ≪ (Island growth time)

$$\alpha \equiv \frac{\delta A_\parallel}{B_0} \qquad \delta\mathbf{B} = \nabla \times (\alpha \mathbf{B_0}) = \nabla\alpha \times \mathbf{B_0} + \alpha(\nabla \times \mathbf{B_0})$$

$$\alpha = \sum_{m,n} \alpha_{(m,n)} \qquad \alpha_{(m,n)} = \Gamma(r)\cos(n\phi - m\theta - \omega t + \xi_0)$$

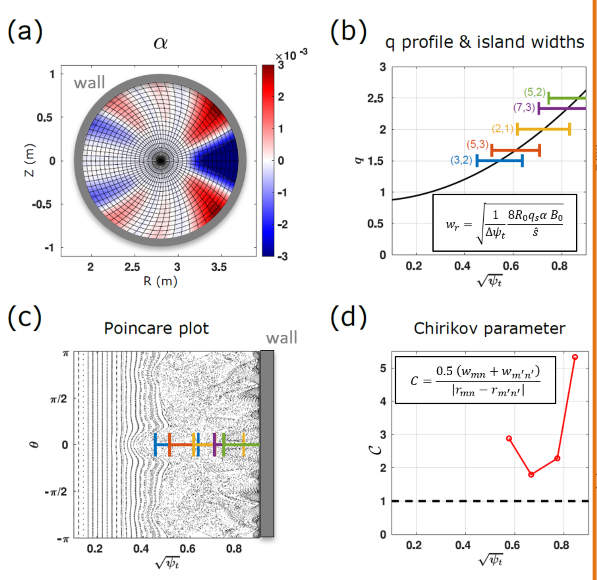
$$(m, n) = [(2,1),(3,2),(4,2),(5,2),(5,3),(6,3),(7,3),(8,3)]$$

$$|\delta B/B_0| \sim 10^{-3}$$

➡ Stochastic layer is produced from $\sqrt{\psi_t} \sim 0.45$

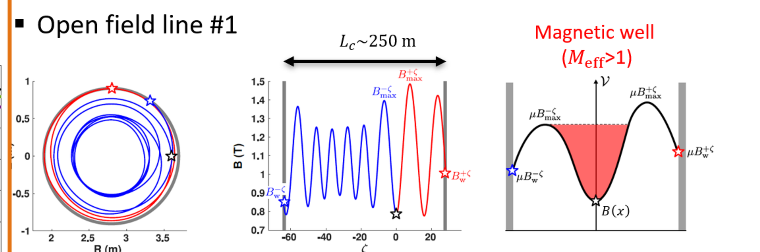
Auto-correlation length of stochastic fields

$$L_{\rm auto} = \pi R_0 / \ln(0.5\pi\mathcal{C}) \approx 5.6\ \mathrm{m}\ \text{when}\ C = 3$$

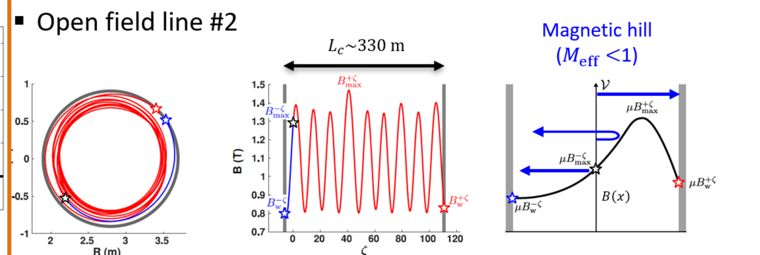



## Connection Length and Magnetic Mirror Ratio

- Open field line #1




- Open field line #2

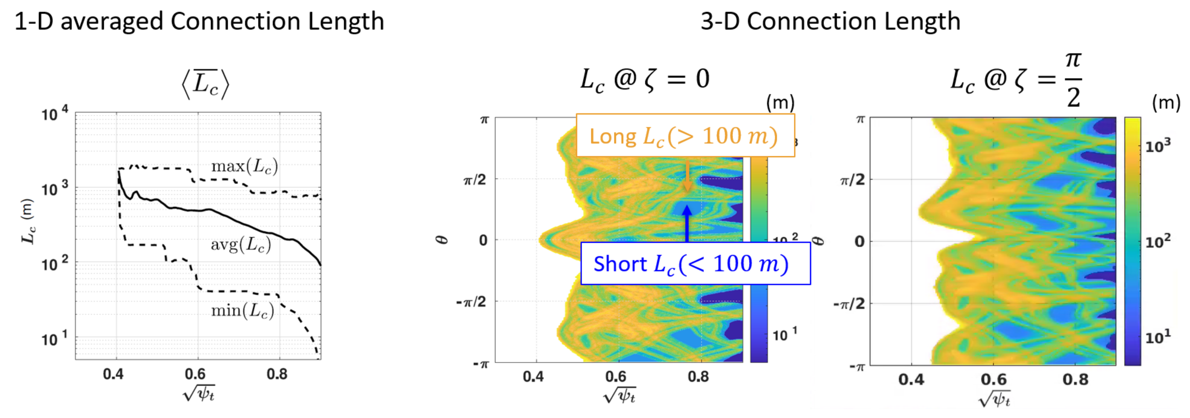



- **Connection Length $L_c$**
  → Passing electron dynamics
  $\tau_\parallel^{\rm pass} \sim \frac{0.5L_c}{v_{\rm th}}$
- **Effective Magnetic Mirror Ratio $M_{\rm eff}$**
  → Trapped electron dynamics
  $M_{\rm eff}(x) \equiv B_{\rm max}^{\rm eff}/B(x)$
  $\left|\frac{v_\parallel(x)}{v_\perp(x)}\right| < \sqrt{M_{\rm eff}(x) - 1}$

➡ $L_c$ and $M_{\rm eff}$ depend on the position
Need to understand ***3-D topology***

## Connection length of open field lines

1-D averaged Connection Length — 3-D Connection Length

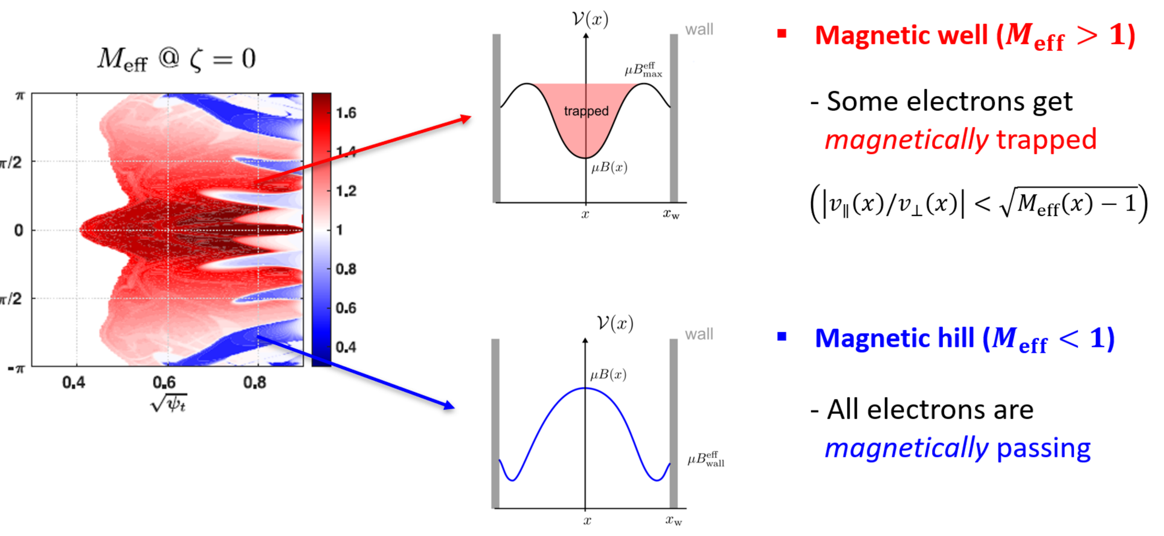



- Connection Length $L_c$ determines passing electron dynamics

$\tau_\parallel^{\rm pass} \sim 0.5L_c/v_{\rm th}$ — Passing electrons:
- Along shorter $L_c$ line → Shorter confinement time
- Along longer $L_c$ line → Longer confinement time

## Electrons can be "trapped" by 3-D magnetic mirror effects

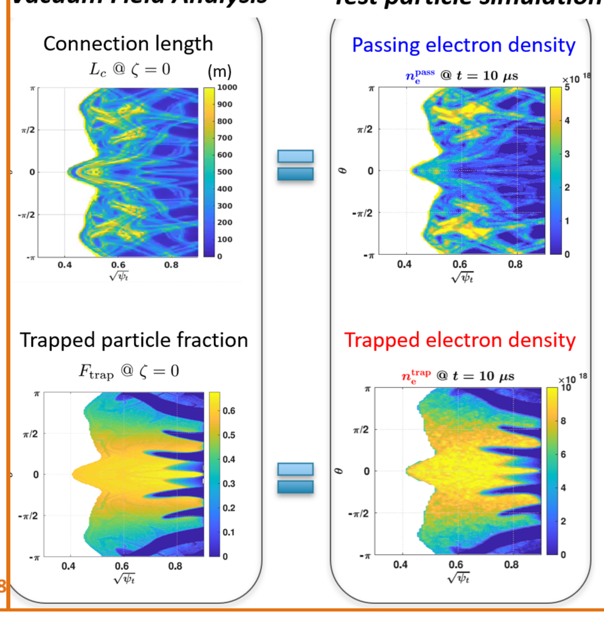
- ***Effective mirror ratio*** $\boldsymbol{M_{\rm eff}}$ determines passing-trapping condition



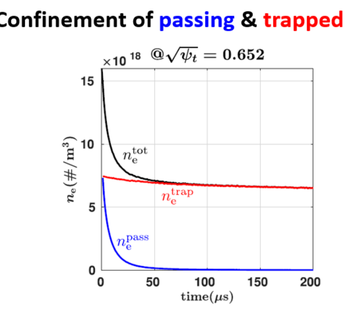

- **Magnetic well ($M_{\rm eff} > 1$)**
  - Some electrons get *magnetically* trapped
  $\left(|v_\parallel(x)/v_\perp(x)| < \sqrt{M_{\rm eff}(x) - 1}\right)$
- **Magnetic hill ($M_{\rm eff} < 1$)**
  - All electrons are *magnetically* passing

## "3-D magnetic topology" well explains the dynamics of test electron particles

***Vacuum Field Analysis*** — ***Test particle simulation***




**Confinement of passing & trapped electrons**

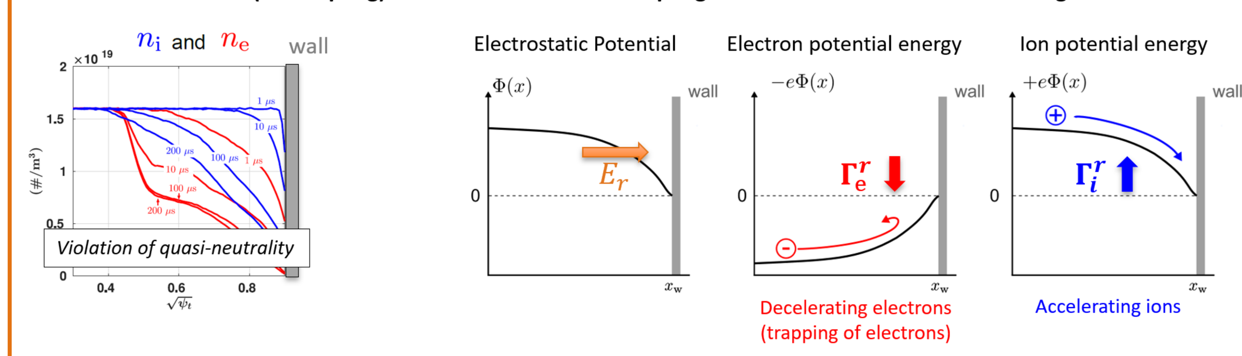



- Higher passing electron density at longer $L_c$ region (short confinement time)
- Magnetically trapped electrons at the magnetic hills (very long confinement time)

➡ However, real plasma dynamics requires ***consistent coupling*** between electrons and ions through ***electric fields***

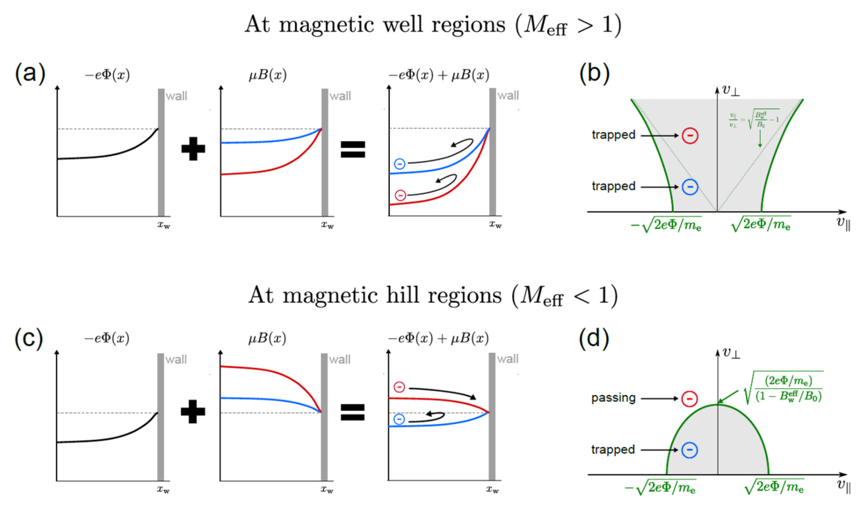
## Most electrons get trapped by the ambipolar potential for the quasi-neutrality

**Test Particle Simulation (no coupling)** — **Consistent coupling between electrons and ions through E field**



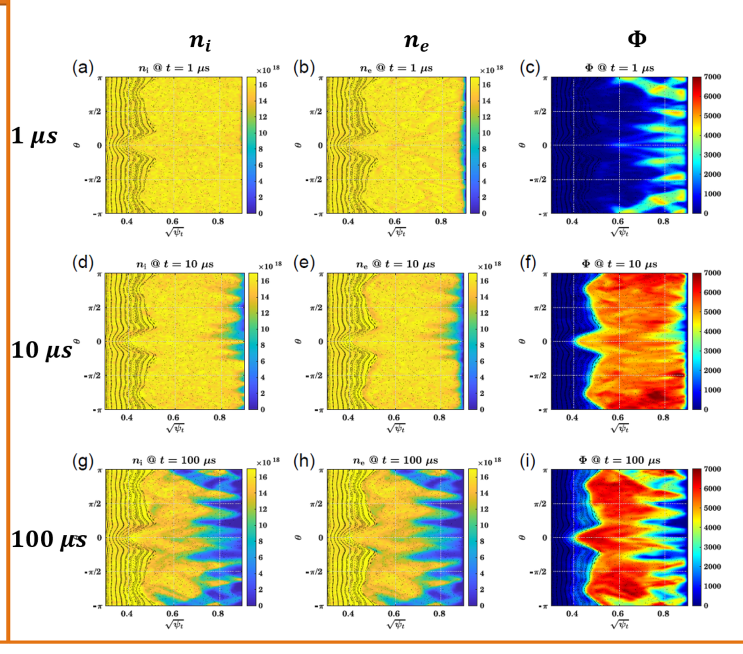

- In test particle simulation, electron density drop is 60 times faster than ion collapse ($v_{th}^e/v_{th}^i = \sqrt{m_i/m_e} \sim 60$)
- The ***positive ambipolar potential*** ($e\Phi \sim T_e$) builds up for the ***ambipolar transports*** ($\boldsymbol{\Gamma_i \approx \Gamma_e}$)
  → Impedes the fast electron loss until it matches with the ion loss
- ***Most electrons get trapped*** by ambipolar electric fields to maintain the ***quasi-neutrality*** ($\boldsymbol{n_i \approx n_e}$)

## High-$\mu$ electrons at the magnetic hill can exit to the wall




- At the **magnetic hill region ($M_{\rm eff} < 1$)**, ***high-$\mu$ electrons can be passing particles***
- These ***kinetic effects*** on passing-trapped electrons must be considered to understand ***electron heat transport***

## Ambipolar potential has a 3-D structure correlated with the connection length

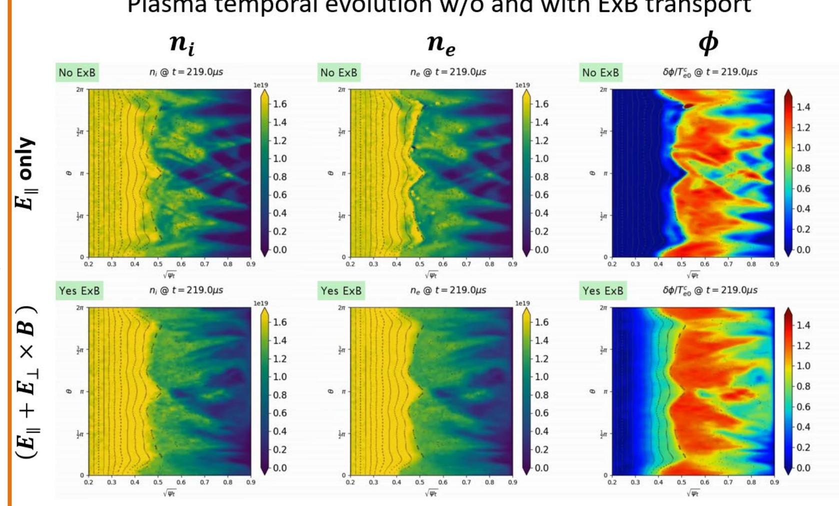



- **Parallel dynamics of plasma transport**
  1. Ambipolar potential builds-up at electron thermal speeds
  2. Plasma collapses at ion sound speeds
     - Ambipolar transport
     - Lower density at shorter $L_c$ regions
  3. 3-D positive ambipolar potential correlates with the connection length structure
     - At *shorter $L_c$* region
       → Lower $n_i$ → Less $n_e^{\rm trap}$ → ***Lower Φ***
     - At *longer $L_c$* region
       → Higher $n_i$ → More $n_e^{\rm trap}$ → ***Higher Φ***

➡ Strong $E_\perp$ is produced between longer and shorter $L_c$ regions

## ExB vortices mix the plasma across the stochastic field lines

Plasma temporal evolution w/o and with ExB transport

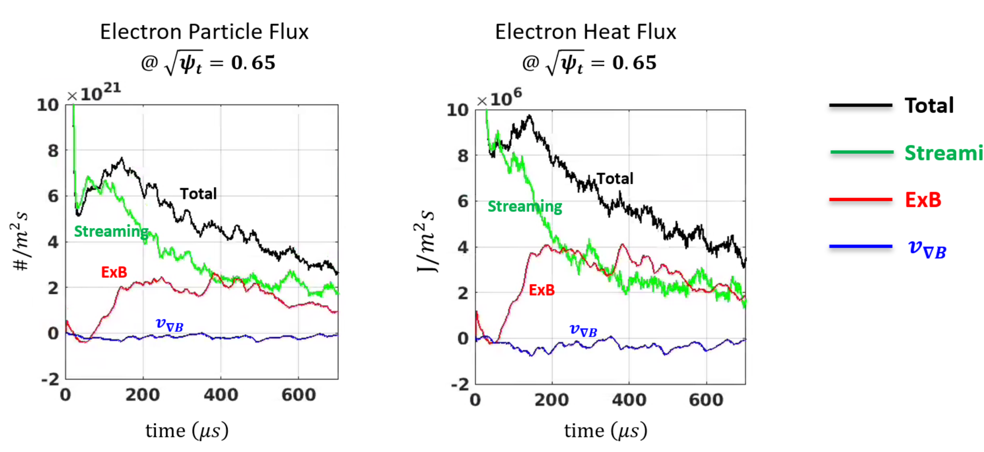



- **Perpendicular dynamics**

Strong $E_\perp$ (by parallel dynamics)
⬇
Fast $E_\perp \times B$ vortices
***Turbulent ExB mixing*** across field lines
→ Deform the plasma structure
→ Enhance radial transport
→ ***Collisionless detrapping*** *of electrons*

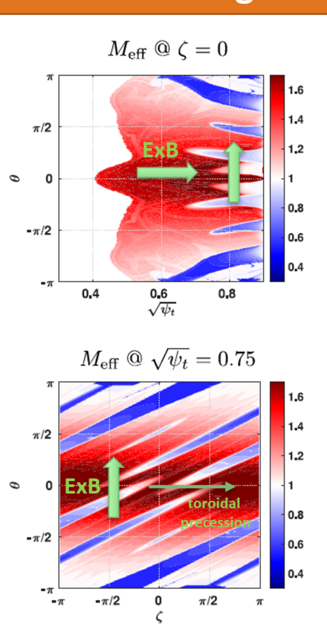
## ExB contributes considerable amounts of electron fluxes

**Electron Radial Fluxes @ $\sqrt{\psi_t} = 0.65$**

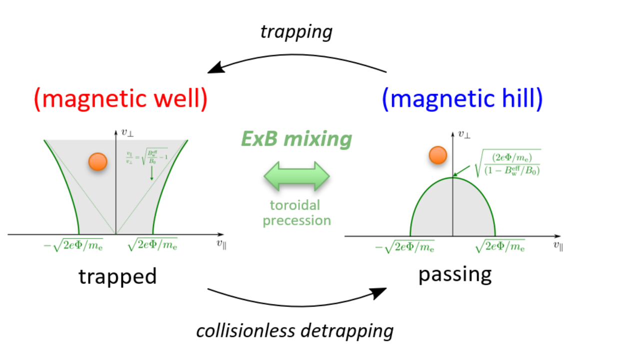



- **ExB transport** contributes about **(30~40)% of particle flux** and **(50~60)% of heat flux**

## ExB mixing enhances collisionless detrapping of high-$\mu$ electron



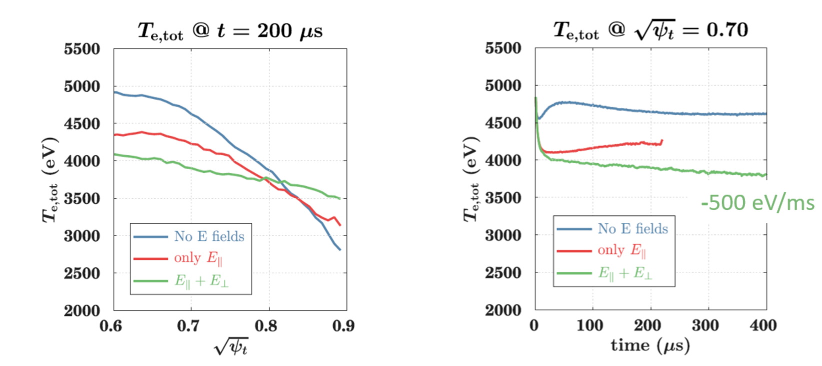

- **Confinement of high-$\mu$ electrons (passing-trapped boundary)**
  - They are well-trapped at magnetic well regions
  - They can exit to the wall at magnetic hill regions by overcoming the electric potential well




➡ ExB carries and mixes the electrons radially and poloidally
***ExB mixing*** enhances the ***collisionless detrapping*** in average

## ExB transport and mixing play crucial roles in decreasing electron temperature steadily

Radial $T_e$ profile — $T_e$ temporal evolution




- ***Trapped particle transport*** is critical for determining the electron thermal transport and temperature
  - (No E field case) and (only $E_\parallel$) cases have saturated electron temperature with higher gradients
  - $(E_\parallel + E_\perp)$ case shows that the electron temperature steadily decrease in the time scale of milliseconds
    - *High-$\mu$ trapped electrons* can be detrapped by ExB mixing and toroidal precession
    - At $\sqrt{\psi_t} = 0.7$ surface, the temperature decreasing rate is about (-500 eV/ms)

## Summary

- Collisionless plasma transport in open stochastic magnetic fields has been studied based on first-principles-based calculations
- A new type of analysis on the **3-D topology of magnetic potential** in the stochastic layer
  - Effective magnetic mirror ratio: magnetic wells and **magnetic hills**
- ***Ambipolar electric fields*** for the quasi-neutrality play critical roles in determining plasma transport
  - $E_\parallel$ makes ambipolar plasma transport that propagates along stochastic fields at ion sound speed
  - $E_\parallel$ and *3-D magnetic mirror ratio* determines the passing-trapped condition of electrons
  - $E_\perp \times B$ radial transport is considerable (particularly for the trapped electrons)
  - $E_\perp \times B$ mixing across the stochastic fields enhances collisionless detrapping of high-$\mu$ trapped electrons
- We observed a considerable degradation of the global plasma profile and electron temperature in the timescale of milliseconds that agrees with the typical time scale of the thermal quench
- Future works
  - Collisional transports
  - Recycling particles
  - More realistic plasma profile and magnetic perturbations