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First systematic theory of ohmic breakdown in a tokamak: a turbulent ExB mixing avalanche

Min-Gu Yoo

Yong-Su Na[2], Jeongwon Lee[3], Young-Gi Kim[2], Jayhyun Kim[3]

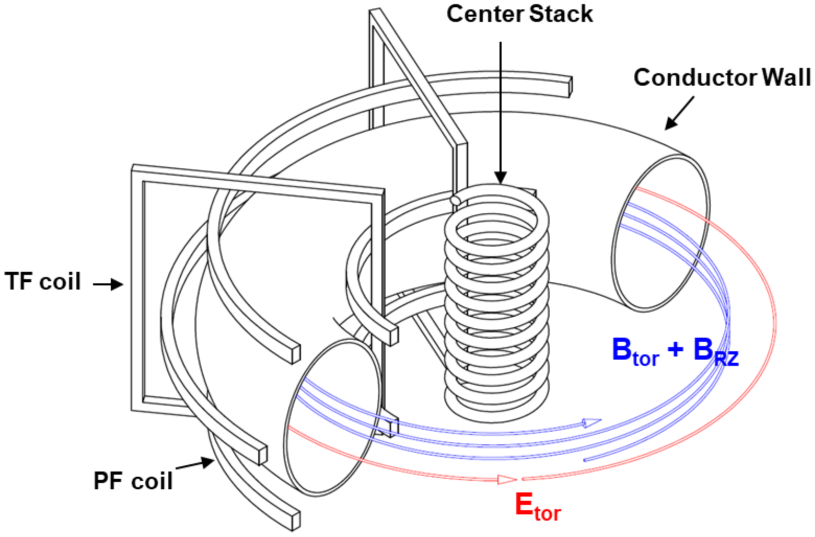
1. Princeton Plasma Physics Laboratory, Princeton, U.S.A.
2. Seoul National University, Seoul, South Korea
3. National Fusion Research Institute, Daejeon, South Korea

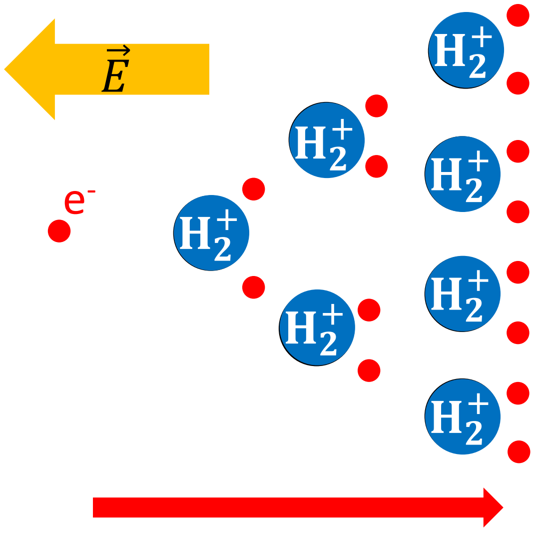
email: myoo@pppl.gov

Contents

What is Ohmic breakdown?

- **What is ohmic breakdown?**
  - A major method to produce initial plasma in the device
  - Electrical breakdown of neutral gas by **toroidal electric fields**





$v_{de} = -\mu_e \, E$

Electron avalanche

Distinct characteristics of Ohmic breakdown

✓ **Open magnetic field lines**

- External magnetic fields are dominant
- Plasma current is negligible

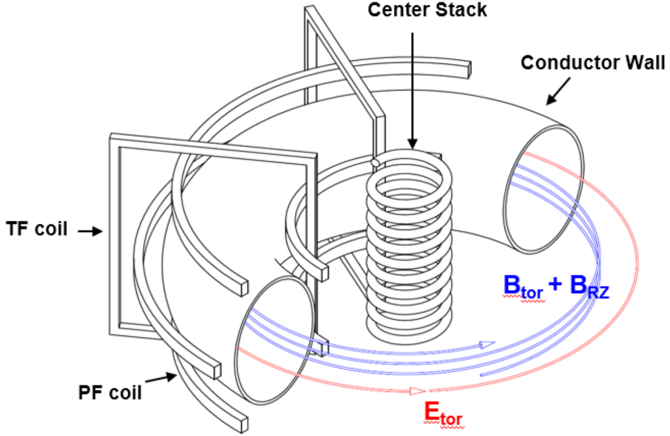
✓ **Very low pitch angle**

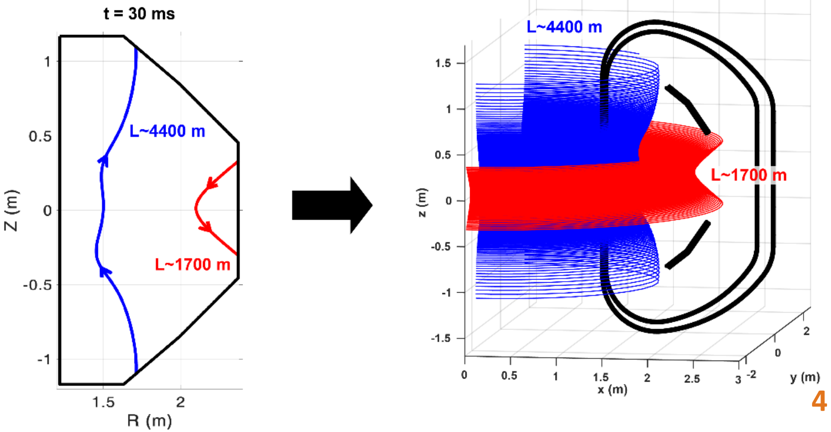
- $\mathrm{B_{RZ}/B_{tor}} \sim 10^{-3}$
- Long connection lengths (> 1000 m)

✓ **Toroidal electric fields**

- $E_{tor} \leq 1\ V/m$
- **Strongest** during normal tokamak operation

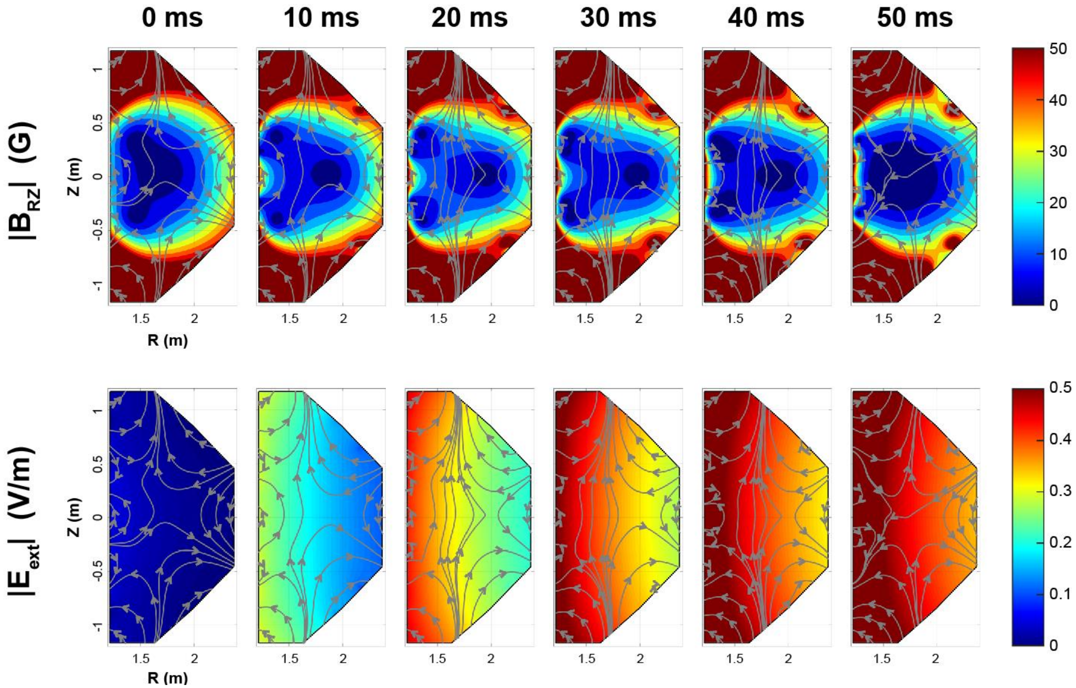
➡ **Underlying physical mechanisms have been obscured for decades**





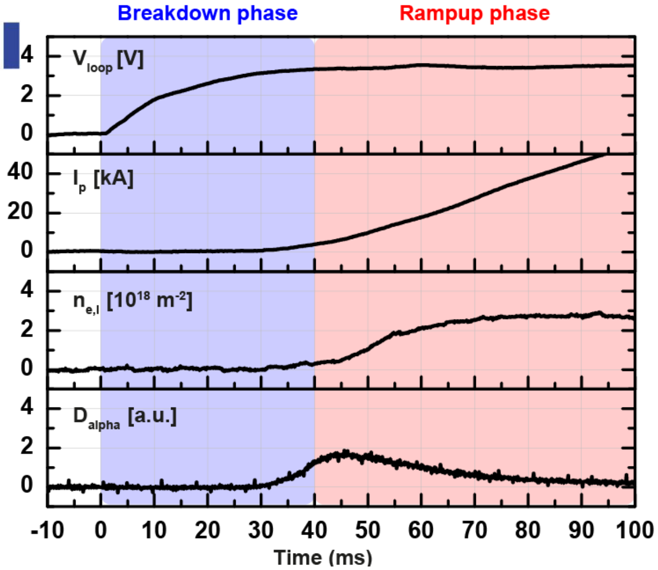
Time-varying complex electromagnetic fields

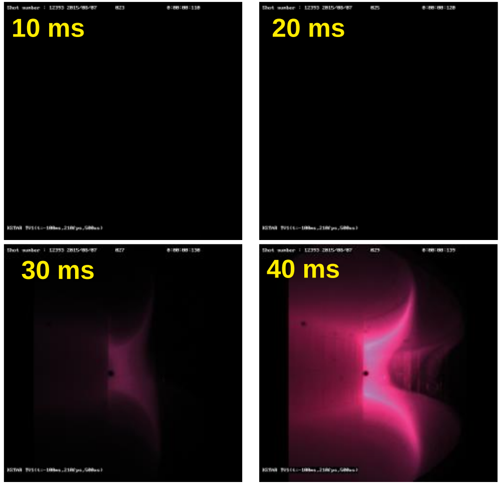
- **(time-varying) CS currents + PF currents + eddy currents**



➡ **Deep understanding of Ohmic breakdown physics is essential to design robust and optimized breakdown scenarios**

Lack of experimental observations





Initial plasma during breakdown

Cold (0.1 - 100 eV)
Rarefied ($10^5 - 10^{17}$ m^{-3})

↔

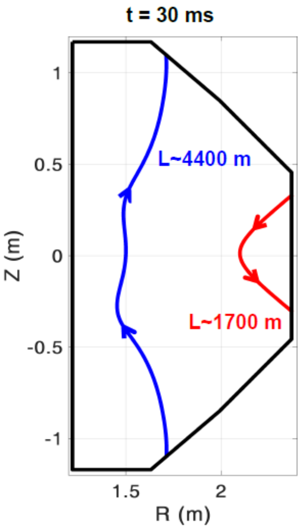
Target plasma of usual diagnostics

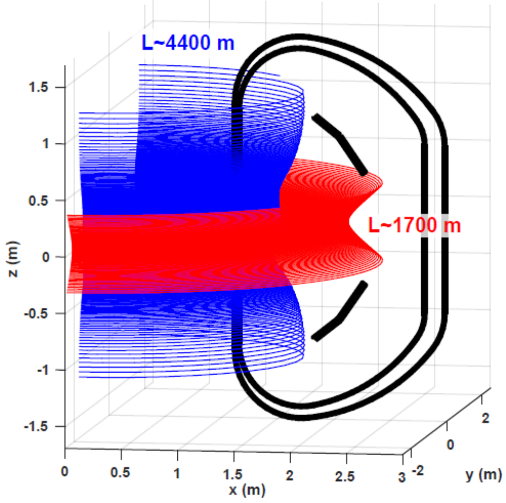
Hot (> 100 eV)
Dense (> 10^{18} m^{-3})

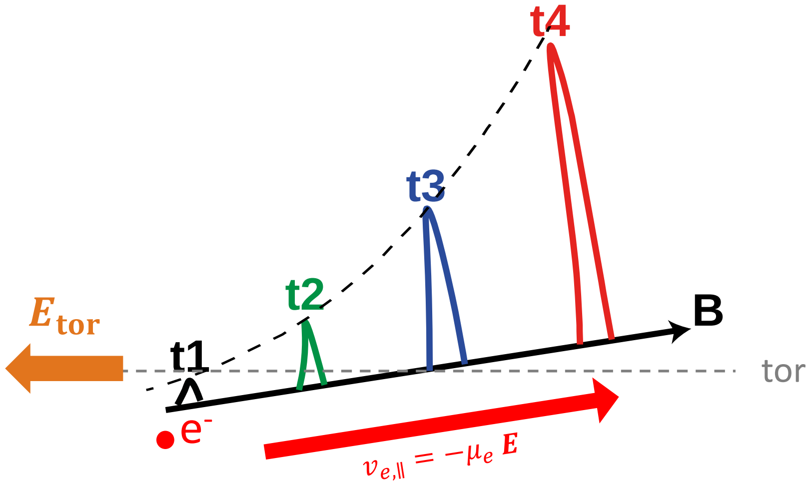
➡ **Experimental observations of ohmic breakdown phenomena are very limited**

Previous physical concept based on Townsend theory

- **Townsend avalanche along B**







1. Parallel electron transport ($v_e^{\parallel}$) is dominant

2. Growth rate is determined by Townsend theory

$$n(x_\parallel) = n_0 \exp(\alpha x_\parallel)$$

$$\alpha = Ap \exp\left(-Bp/E_\parallel\right)$$

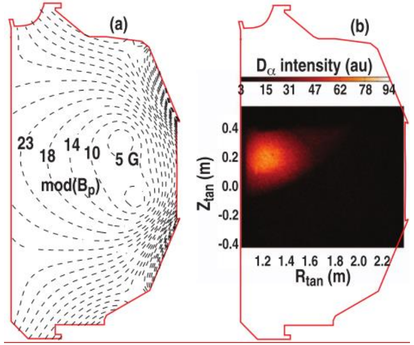
[1] Townsend, J. S. Electricity in Gases. (Рипол Классик, 1915).

Field quality analyses of external EM structure

Based on the Townsend avalanche theory…

- Electron avalanche physics are determined by external fields only
- Detail avalanche physics are out of interest
- Evaluations of complex external electromagnetic fields are important

[6]



Field quality analysis

0D effective parameters [4]

$$L_{\mathrm{eff}} \cong 0.25\, a_{\mathrm{eff}} B_T / B_p$$

Empirical condition [5]

$$E_T B_T / B_\perp > 1000\ \mathrm{V/m}$$

2D field-line-integration [6,7]

$$L = \int_{\vec{B}} dl \qquad V = \int_{\vec{B}} \vec{E} \cdot d\vec{l}$$

All of these considerations are well known and we find that

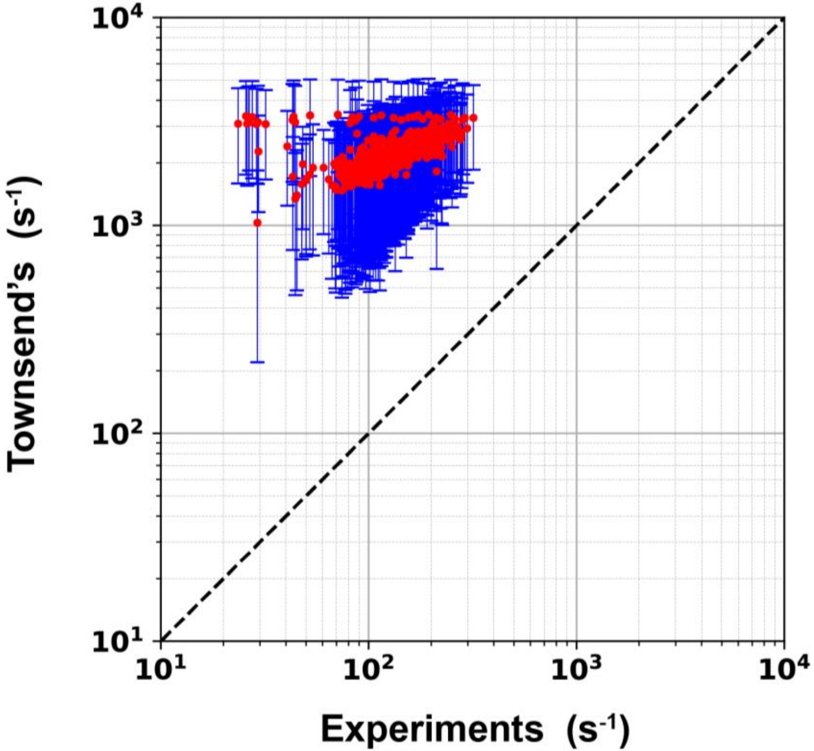
there are no new physics issues related to achieving plasma initiation in an ITER class tokamak.

[ITER Physics Basis (1999)]

[4] R. Yoshino, *et al.*, Plasma Phys. Control. Fusion **39** 205 (1997)
[5] Tanga, A., in Tokamak Start-up (ed. U. Knoepfel), Plenum Press, New York 159 (1986)
[6] Lazarus E.A., *et al.,* Nucl. Fusion **38** 1083 (1998)
[7] G.L. Jackson, *et al.*, POP **17** 056116 (2010)

Mystery 1: Very slow avalanche growth rates in the experiments

Relative growth rates $\left(\frac{1}{n_e}\frac{dn_e}{dt}\right)$



- For 950 shots of KSTAR ohmic breakdown plasma

KSTAR

- Experimental growth rate

$$\frac{1}{n_e}\frac{dn_e}{dt} \approx \frac{1}{I_p}\frac{dI_p}{dt}$$

- Townsend avalanche

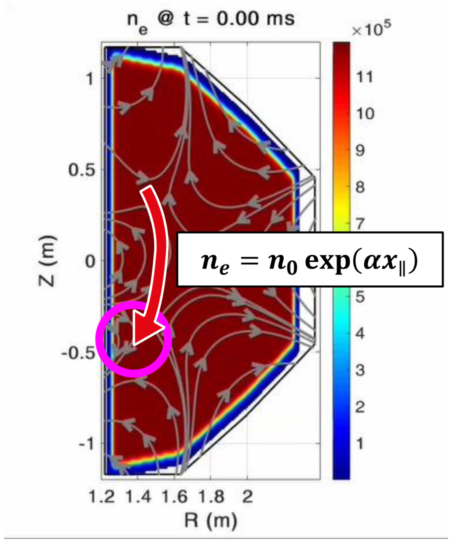
$$\frac{1}{n_e}\frac{dn_e}{dt} = \left(\alpha - \frac{1}{L_{\mathrm{eff}}}\right)v_{de} \qquad \alpha = 510\,p\exp\left(-\frac{1.25\times10^4 p}{E}\right)$$

$$v_{de} = 43(E/p)$$

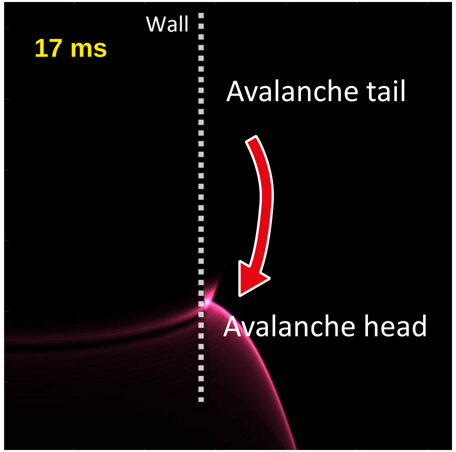
➡ **Experimental growth rates are 10-100 times slower than Townsend's predictions**

Mystery 2: Homogeneous plasma structure along B field line

Townsend avalanche simulation

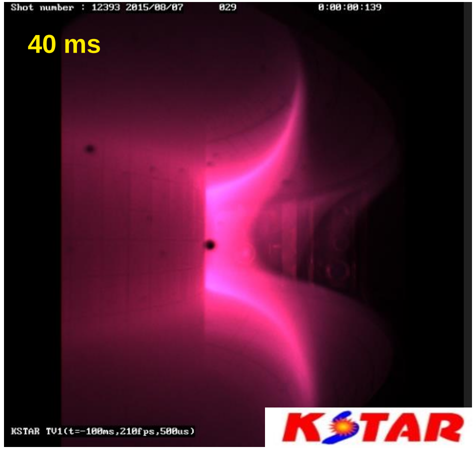


Calculated Hα image



Visible camera from Experiment

Observed Hα image



Localized & asymmetric structure

(Exponential density profile along $\vec{B}$)

Elongated & symmetric structure

(Homogeneous density along $\vec{B}$)

One-way parallel electron transport (Townsend theory)
cannot make homogeneous structure along B

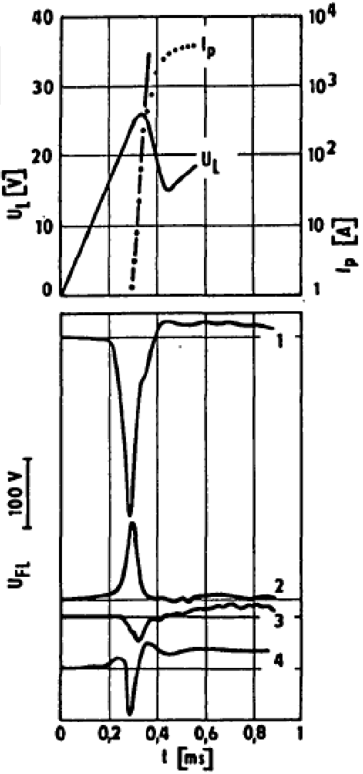
What is the missing physics?

- **Townsend theory is not valid for ohmic breakdown**
  - High plasma potential build-up was observed 30 years ago
  - Townsend theory cannot explain spatial-temporal plasma evolution

- **The missing physics is the “plasma response”**
  - Townsend theory ignored any plasma response
  - Plasma responses play crucial roles in many discharges such as streamer and lightening

- **A systematic theory considering plasma response in the complex EM topology is required to understand ohmic breakdown physics**

M. Valovic, *Nucl. Fusion* (1987)



Research Scope

- **Approaches**
  - **Toroidally symmetric plasma response model**
    - Provides a simple and clear understanding of the ohmic breakdown physics
  - **BREAK** (**B**reakdown **R**ealistic **E**volution **A**nalysis in tokama**K**)

    M.-G. Yoo, *CPC*, 221 (2017) 143–159

    - Multi-dimensional particle simulation based on the first-principle
    - Realistic plasma evolution in a complex electromagnetic topology

- **Discovery of fundamental physical mechanism of the ohmic breakdown**

M.-G. Yoo, *Nat. Commun.* (2018) 9:3523

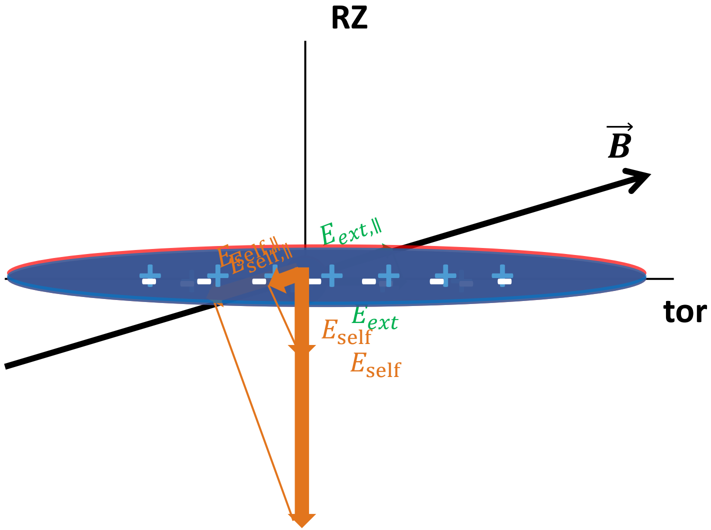
Townsend avalanche → **Turbulent ExB mixing avalanche**

Plasma response

Toroidally symmetric plasma response

$$\boldsymbol{E} = -\frac{\partial \boldsymbol{A}}{\partial t} - \nabla V = \boldsymbol{E}_{\mathbf{ext}} + \boldsymbol{E}_{\mathbf{self}}$$

self-electric fields



- $\boldsymbol{n} \ll \boldsymbol{n_c}$ (low density)

  $|\boldsymbol{E}_{\mathbf{self},\parallel}| \ll |\boldsymbol{E}_{\mathbf{ext},\parallel}|$ ⇒ Self-electric fields are negligible

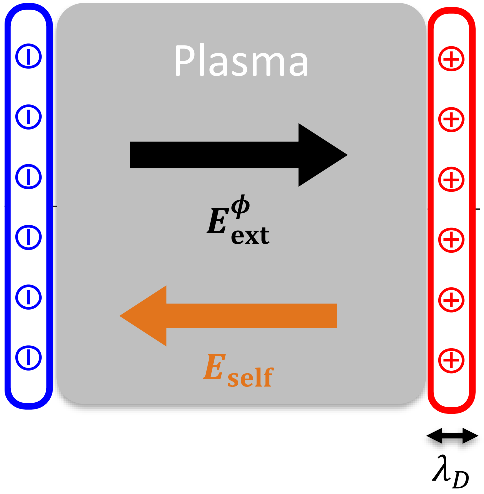
- $\boldsymbol{n} \gtrsim \boldsymbol{n_c}$ (high density)

  $|\boldsymbol{E}_{\mathbf{self},\parallel}| \sim |\boldsymbol{E}_{\mathbf{ext},\parallel}|$ ⇒ Total electric fields is reduced ($E_{\text{tot},\parallel} = E_{\text{ext},\parallel} + E_{\text{self},\parallel} \rightarrow 0$)
  $|\boldsymbol{E}_{\mathbf{self},\perp}| \gg |\boldsymbol{E}_{\mathbf{ext},\perp}|$ ⇒ $\vec{E} \times \vec{B}$ drift motions

➡ **Self-electric fields** play significant roles in the ohmic breakdown regarding **parallel** and **perpendicular** dynamics

Toroidally symmetric plasma response

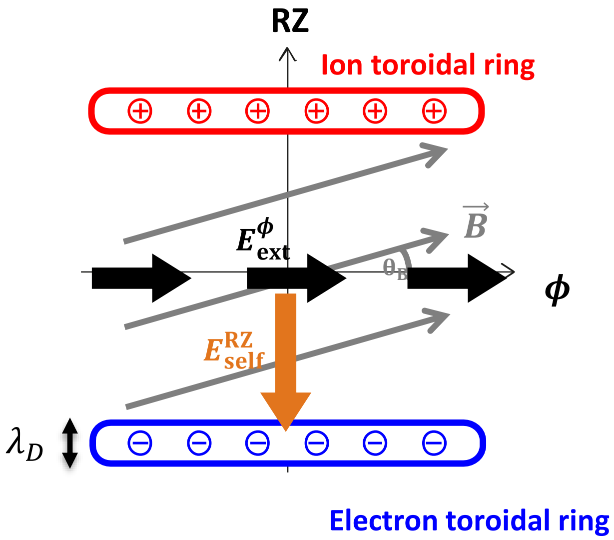
Simple 1D case



$$E_{\mathrm{tot}} = E_{\mathrm{ext}} + E_{\mathrm{self}} \approx 0$$

Plasma response = Debye shielding

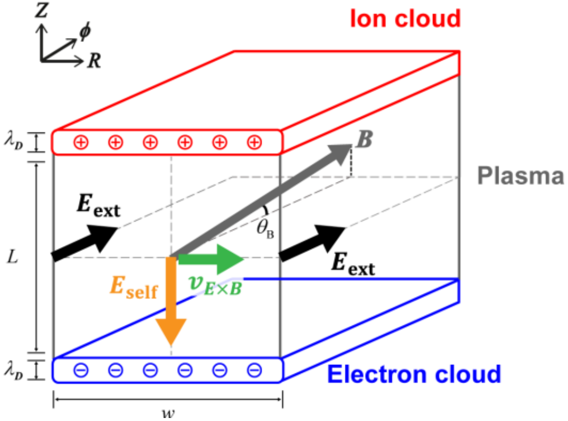
Tokamak case
(toroidal periodicity)



$$E_{\mathrm{tot},\parallel} = E_{\mathrm{ext},\parallel}^{\phi} + E_{\mathrm{self},\parallel}^{RZ} \approx 0$$

Debye shielding via n=0 poloidal electric fields (E_{self}^{RZ})

Derivation of critical plasma densities ($n_{\mathrm{crit},\parallel}$ and $n_{\mathrm{crit},\perp}$)



- **Self-electric field produced by charge separation within Debye length scale**

$$E^{z}_{\mathrm{self}} \approx \sqrt{\frac{nkT_e}{\epsilon_0}}\gamma$$

$$\gamma \approx \left(\frac{2}{\pi}\right)\tan^{-1}\left(\frac{w}{L}\right) \qquad \begin{array}{l}\gamma \to 1 \text{ when } w \gg L \\ \gamma \to 0 \text{ when } w \ll L\end{array}$$

- **Parallel critical density $n_{\mathrm{crit},\parallel}$**

$$E^{Z,\parallel}_{\mathrm{self}} \geq E^{\phi,\parallel}_{\mathrm{ext}}$$

$$\sqrt{\frac{nkT_e}{\epsilon_0}}\gamma \sin\theta_B \geq E^{\phi,\parallel}_{\mathrm{ext}} \cos\theta_B$$

$$n \geq \left(\frac{\epsilon_0}{kT_e}\right)\cot^2\theta_B \left(E^{\phi}_{\mathrm{ext}}\right)^2 \left(\frac{1}{\gamma}\right)^2 \equiv \boldsymbol{n_{\mathrm{crit},\parallel}}$$

- **Perpendicular critical density $n_{\mathrm{crit},\perp}$**

$$v^{RZ}_{\mathrm{E}\times B} \geq v^{RZ}_{\mathrm{th},e}$$

$$\sqrt{\frac{nkT_e}{\epsilon_0}}\gamma\frac{\cos\theta_B}{B} \geq \sqrt{\frac{kT_e}{m_e}}\sin\theta_B$$

$$n \geq \frac{\epsilon_0 B^2}{m_e}\tan^2\theta_B\left(\frac{1}{\gamma}\right)^2 \equiv \boldsymbol{n_{crit,\perp}}$$

Parallel response: $E_{\parallel}$ reduction

- **Separation force ($E^{\phi,\parallel}_{\mathrm{ext}}$) vs. Attracting force ($E^{RZ,\parallel}_{\mathrm{self}}$)**

$$E^{\phi,\parallel}_{\mathrm{ext}} = \boldsymbol{E}^{\boldsymbol{\phi}}_{\mathbf{ext}} \cos(\theta_B) \qquad E^{RZ,\parallel}_{\mathrm{self}} = -\boldsymbol{E}^{\mathbf{RZ}}_{\mathbf{self}} \sin(\theta_B)$$

- **Equilibrium state in parallel direction**

$$E^{\phi,\parallel}_{\mathrm{ext}} = -E^{\mathrm{RZ},\parallel}_{\mathrm{self}} \quad \Rightarrow \quad \left|\boldsymbol{E}^{\mathbf{RZ}}_{\mathbf{self}}\right| = \left|\boldsymbol{E}^{\boldsymbol{\phi}}_{\mathbf{ext}}\right| \cot(\theta_{\mathrm{B}})$$

(1000 V/m) **(1 V/m)**

- **Cancellation of external electric fields**

$$\boldsymbol{E}^{\parallel}_{\mathbf{tot}} = E^{\phi,\parallel}_{\mathrm{ext}} + E^{\mathrm{RZ},\parallel}_{\mathrm{self}} \approx 0$$

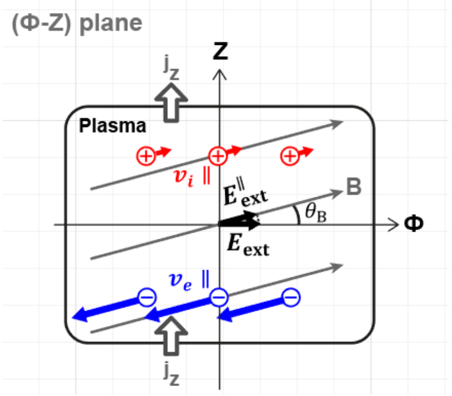
Parallel transport ↓

Heating power ↓

Electron temperature ↓

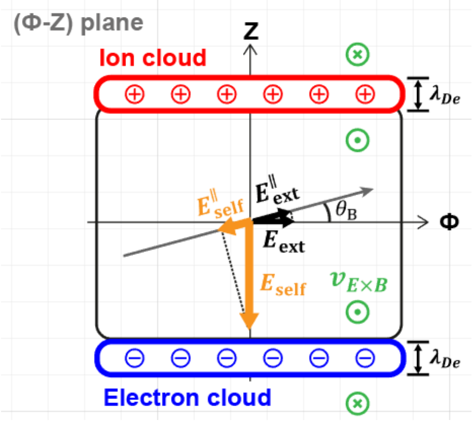
Avalanche growth rate ↓

→ **Key mechanism for slow plasma formation**

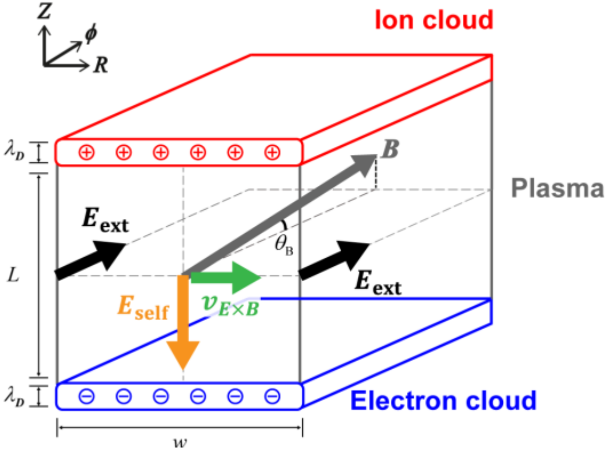


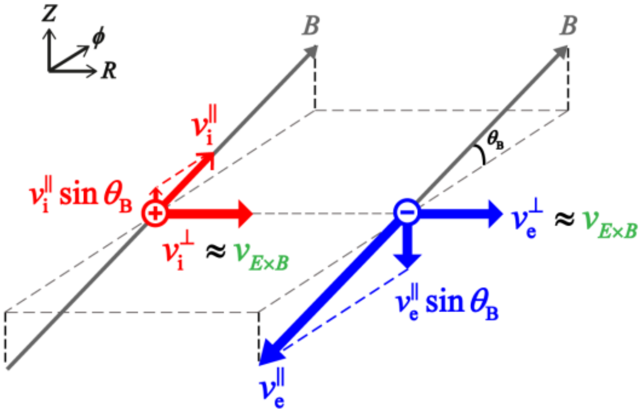
Parallel critical density

$$n_{c,\parallel} \equiv \left(\frac{\epsilon_0}{kT_e}\right) \cot^2(\theta_{\mathrm{B}})(E_{\mathrm{ext}})^2 \left(\frac{1}{\gamma}\right)^2$$



Derivation of critical plasma densities ($n_{\mathrm{crit},\parallel}$ and $n_{\mathrm{crit},\perp}$)





- ✓ **ExB perpendicular transport** is dominant transports in the RZ plane due to very low pitch angle ($\sin\theta_B \sim 10^{-3}$)

$$\underbrace{v_e^{\perp} \approx v_i^{\perp} \approx v_{E\times B}}_{1000\ m/s} \gtrsim \underset{\overset{\uparrow}{1000\ m/s}}{v_e^{\parallel}\sin\theta_B} \gg \underset{\overset{\uparrow}{1\ m/s}}{v_i^{\parallel}\sin\theta_B}$$

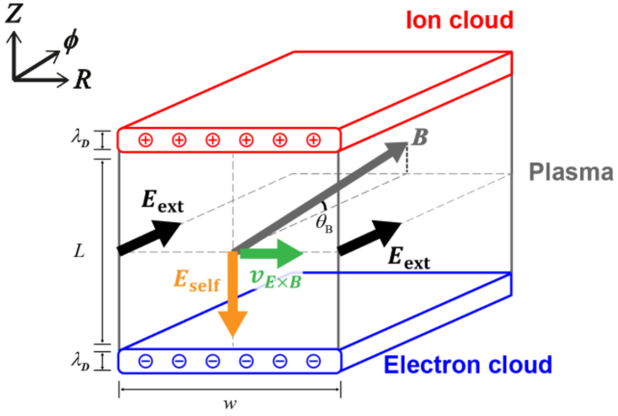
- **Perpendicular critical density $n_{\mathrm{crit},\perp}$**

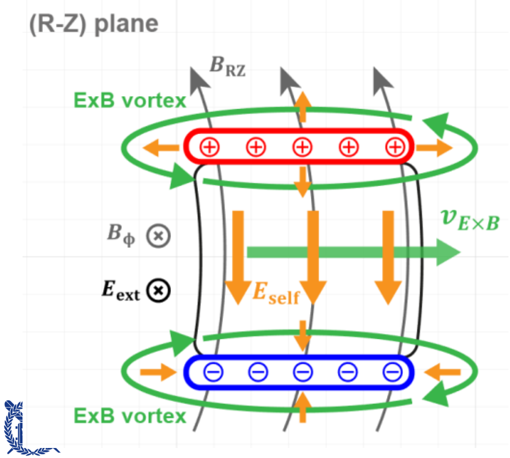
$$v_{E\times B}^{RZ} \geq v_{\mathrm{th},e}^{RZ}$$

$$\sqrt{\frac{nkT_e}{\epsilon_0}}\gamma\frac{\cos\theta_B}{B} \geq \sqrt{\frac{kT_e}{m_e}}\sin\theta_B$$

$$n \geq \frac{\epsilon_0 B^2}{m_e}\tan^2\theta_B\left(\frac{1}{\gamma}\right)^2 \equiv n_{crit,\perp}$$

Perpendicular response: dominant ExB transport





✓ Mean ExB across B_{RZ}

- ➔ Induced by spatial-temporal average $\overline{E^{RZ}_{\text{self}}}$
- ➔ Determine overall plasma flow and position

$$\left\langle \overline{\mathbf{E}^{RZ}_{\text{self}}} \right\rangle = \left|\mathbf{E}^{\phi}_{\text{ext}}\right| \cot\theta_B \left(-\hat{\mathbf{E}}^{\phi}_{\text{ext}} \cdot \hat{\mathbf{B}}_{\phi}\right) \hat{\mathbf{B}}_{RZ}$$

$$\left\langle \overline{\mathbf{v}^{RZ}_{E\times B}} \right\rangle = \frac{\left\langle \overline{\mathbf{E}^{RZ}_{\text{self}}} \right\rangle \times \hat{\mathbf{B}}_{\phi}}{B} = \frac{\left|\mathbf{E}^{\phi}_{\text{ext}}\right|}{\left|\mathbf{B}_{RZ}\right|} \cos\theta_B \left(\hat{\mathbf{E}}^{\phi}_{\text{ext}} \times \hat{\mathbf{B}}_{RZ}\right)$$

✓ Turbulent ExB mixing along B_{RZ}

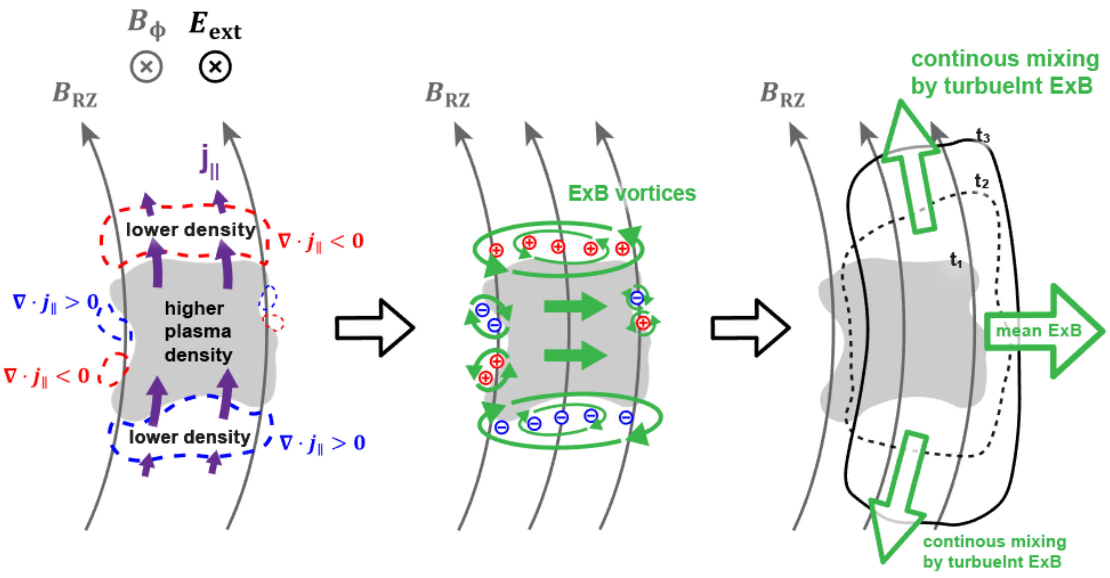
- ➔ ExB vortices at plasma edges are **turbulent** due to negligible viscosity
- ➔ Plasma rapidly diffuses along B_{RZ} by turbulent mixing

$$\nabla \times \mathbf{v}_{E\times B} \approx -\rho / (\varepsilon_0 B)\hat{\mathbf{b}}$$

➡ **Dominant transport mechanism in the RZ plane**

when $n > n_{\text{crit},\perp} \equiv \left(\frac{\epsilon_0 B^2}{m_e}\right) \tan^2(\theta_B) \left(\frac{1}{\gamma}\right)^2$

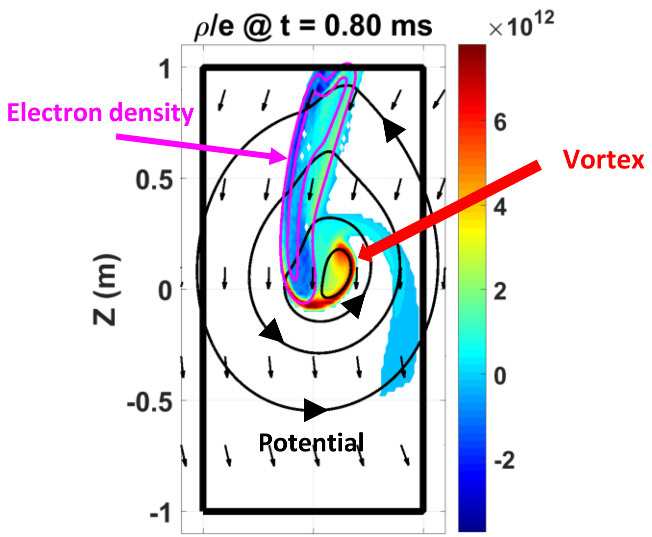
Turbulent ExB mixing along B_{RZ} & mean ExB across B_{RZ}



Charge accumulations via non-unifrom parallel currents

Turbulent ExB vortices formation corresponding to charge densities

Density homogenization along B_{RZ} & Cross transports by mean ExB



ExB mixing avalanche mechanism

Parallel dynamics

$$n > n_{c,\parallel} \equiv \left(\frac{\epsilon_0}{kT_e}\right)\cot^2(\theta_B)(E_{ext})^2\left(\frac{1}{\gamma}\right)^2$$

1. Cancellation of $E_{ext,\parallel}$

   ➔ Slow avalanche growth
   (Mystery 1 solved)

Perpendicular dynamics

$$n > n_{c,\perp} \equiv \left(\frac{\epsilon_0 B^2}{m_e}\right)\tan^2(\theta_B)\left(\frac{1}{\gamma}\right)^2$$

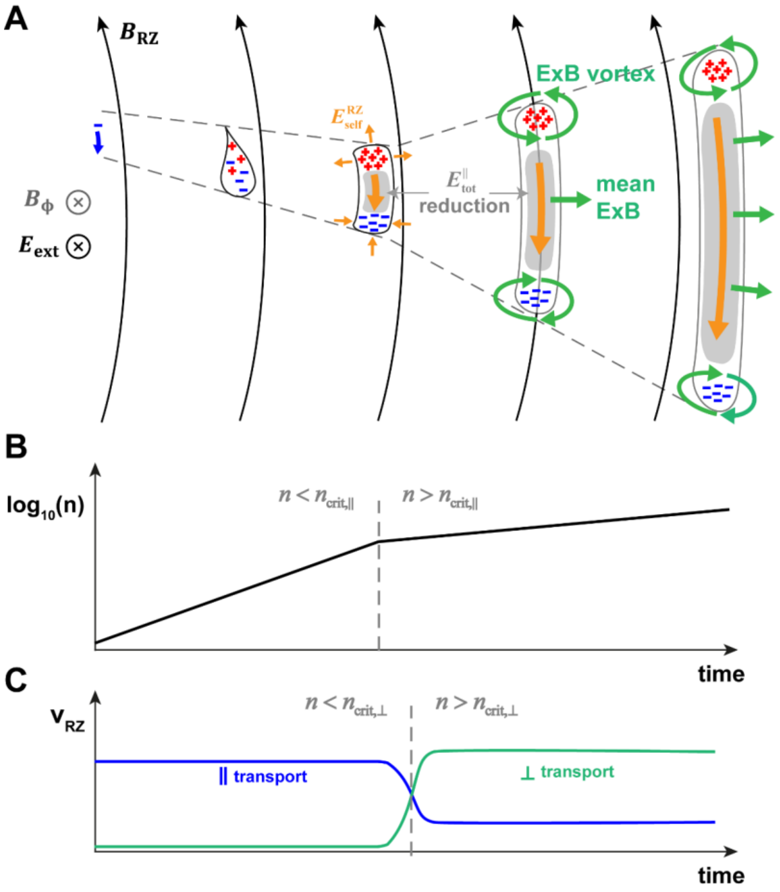
2. Mean ExB across B_{RZ}

   ➔ Determine plasma position

3. Turbulent ExB mixing along B_{RZ}

   ➔ Homogeneous plasma density along B_{RZ}
   (Mystery 2 solved)

   ➔ Dominant plasma loss term
   (Mystery 1 solved)



Development of particle simulation code

- **To study the ohmic breakdown physics under a realistic complicated situation by considering the self-electric fields and kinetic effects consistently**

- **The ohmic breakdown phenomena span a broad range of spatio-temporal scales**

  - $\Delta x \sim (10^{-6} - 1)\ \mathrm{m}\,,\ \ \Delta t \sim (10^{-12} - 10^{-2})\ \mathrm{s}$

- **BREAK** (**B**reakdown **R**ealistic **E**volution **A**nalysis in tokama**K**)

M.-G. Yoo, *CPC*, 221 (2017) 143–159

  - **Written in C/C++ language**
  - **2D / 3D implicit electrostatic particle-in-cell simulation code**
  - **Direct implicit method with D1 damping scheme is adopted to calculate charged particle motion**
  - **6 species (e, H_2^+, H^+, H_3^+, $H_{2(fast)}$, $H_{(fast)}$) are considered**
  - **26 collision reactions in the energy range of (0.01 – 1000) eV and plasma-wall interactions are treated by the MCC (Monte Carlo Collision) scheme**
  - **Coulomb collision is calculated by Nanbu’s method**
  - **Self-electric fields produced by plasma space charge are calculated**
  - **Hybrid parallel computing method (MPI + OpenMP)**

Simulation of the simple ohmic breakdown scenario

- **Magnetic fields**

  $B_{\mathrm{tor}} \sim 3\ \mathrm{T}$ (~1/R dependency)

  $B_{\mathrm{RZ}} \sim 10\ \mathrm{G}$ (Curved shape)

- **Electric fields**

  Uniform loop voltage (10 V)

  $E_{\mathrm{tor}}{\sim}0.6\ \mathrm{V/m}$ (~1/R dependency)

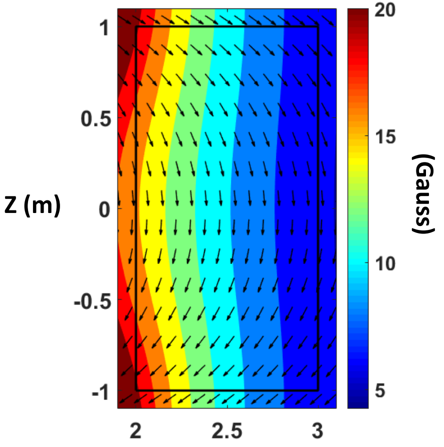
- **Initial condition**

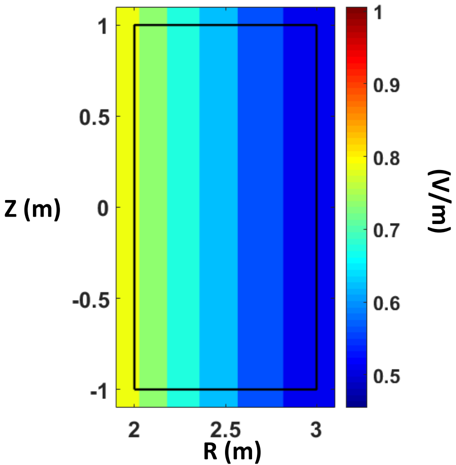
  $n_{e0} = n_{i0} = 10^6\ m^{-3}$ $T_{e0} = T_{i0} = 0.03\ \mathrm{eV}$

- **2 different simulations**

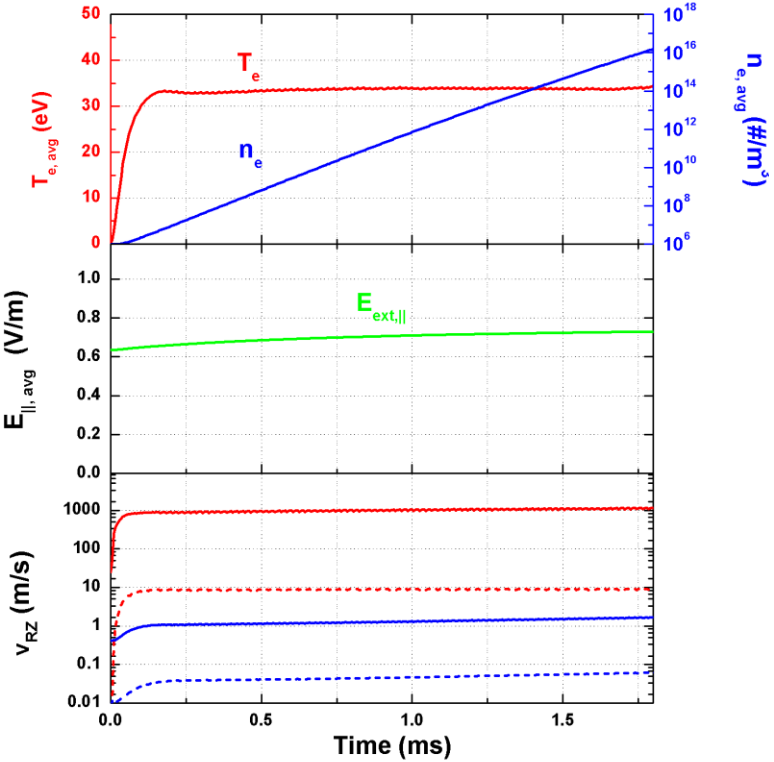
w/o self-electric fields ⟷ **with self-electric fields**

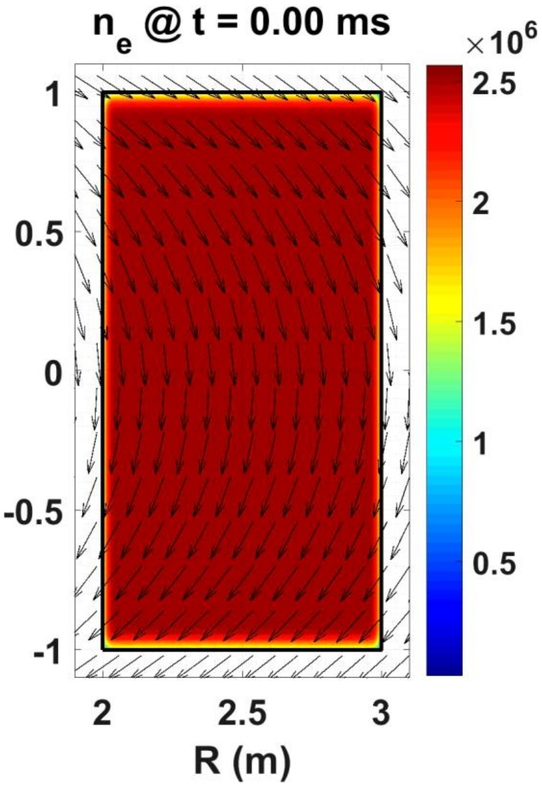
difference





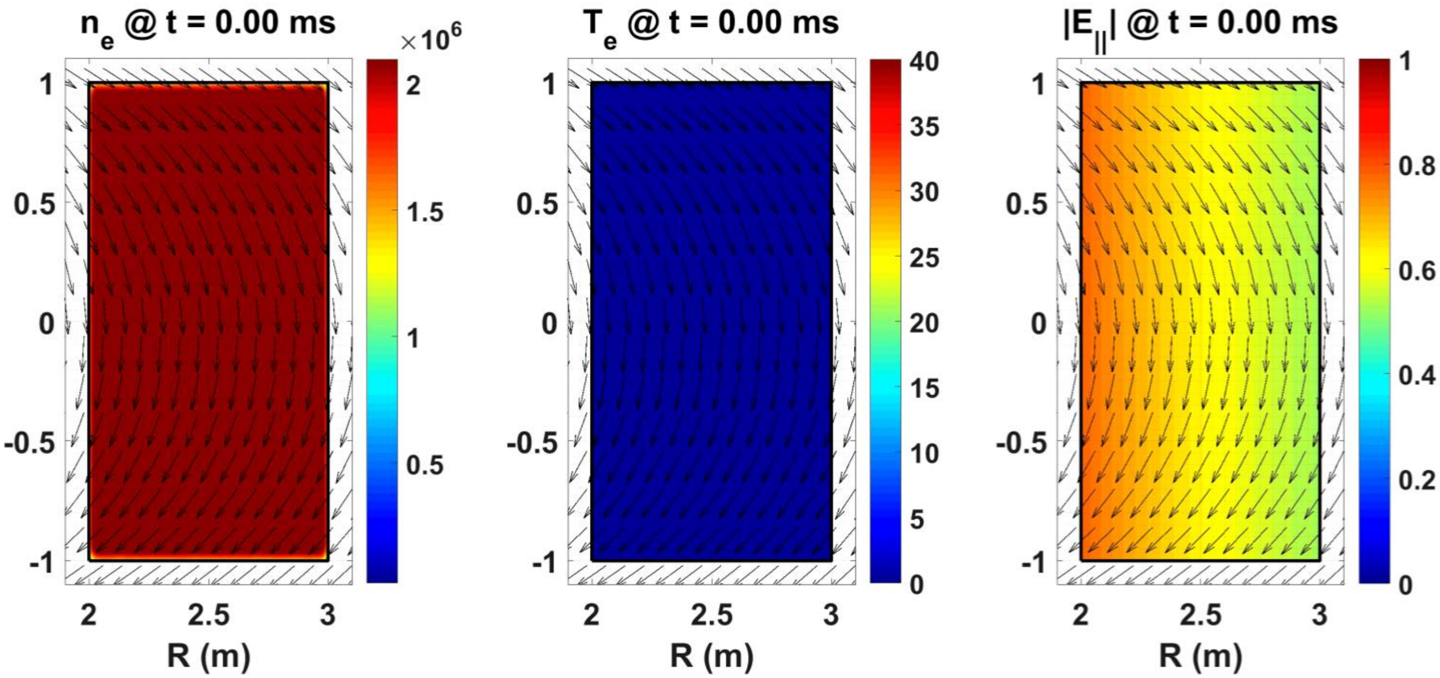
Without self-electric fields (Townsend avalanche)





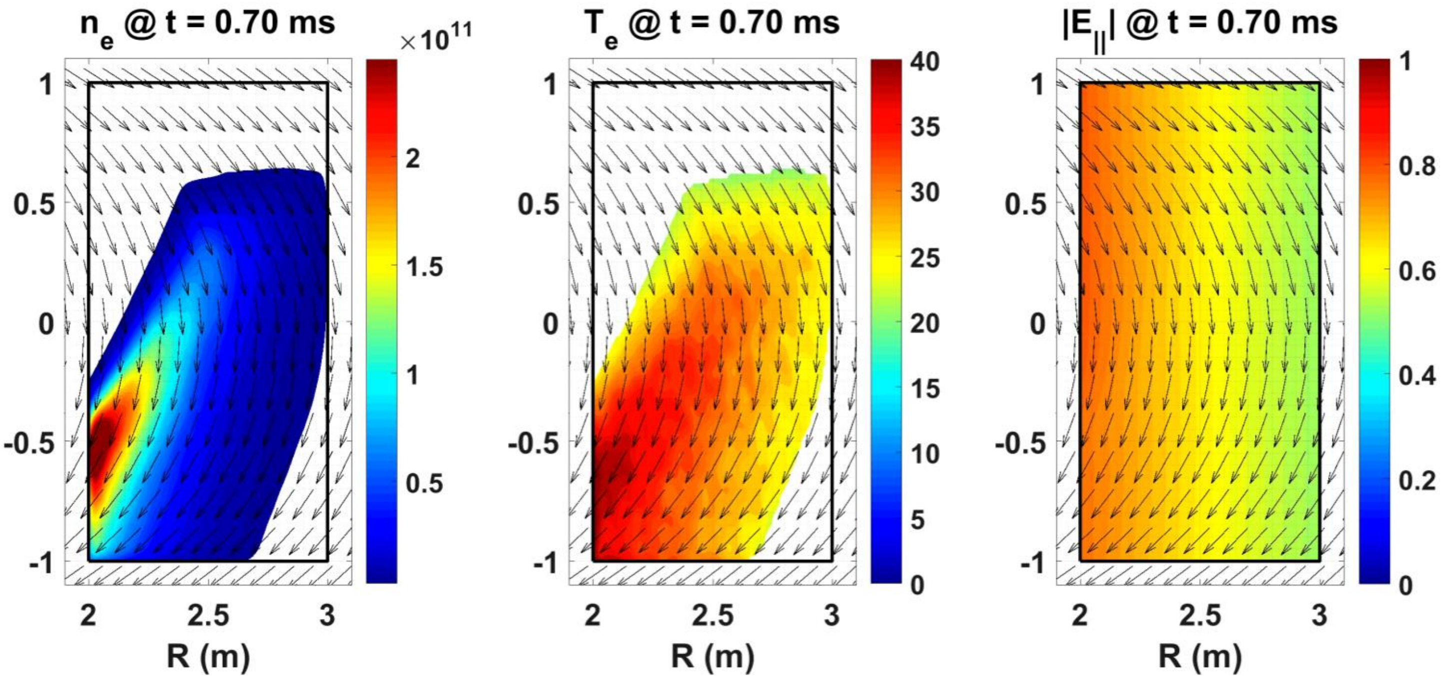
- ✓ Fast growth rate
- ✓ Localized structure
- ✓ Townsend avalanche

Phase 1 : Townsend avalanche



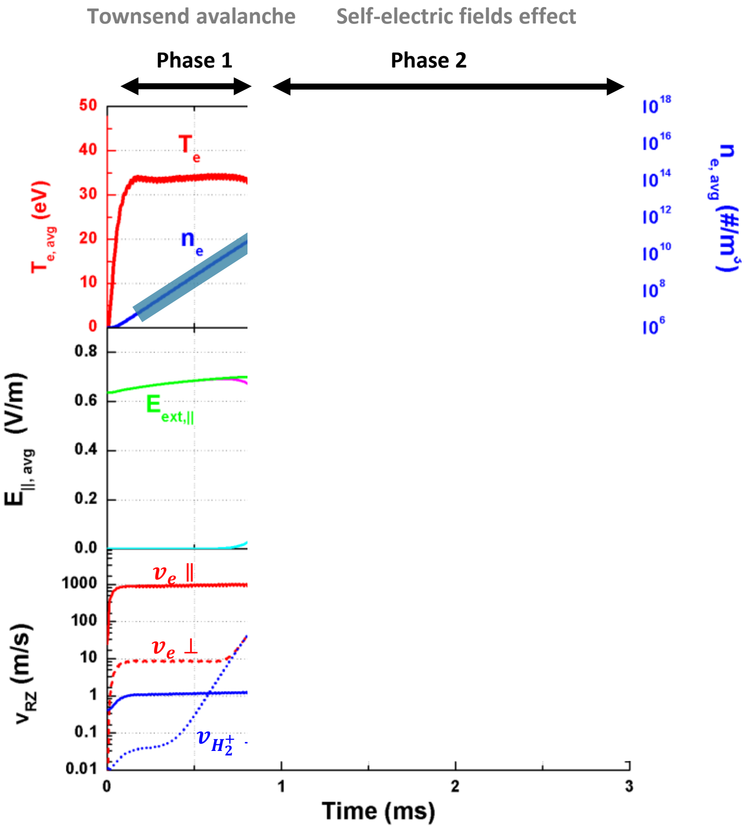
- ✓ **Fast growth rate**
- ✓ **Localized** & **up-down asymmetric structure** due to **parallel electron transport**

Phase 2 : Turbulent ExB mixing avalanche



- ✓ **Slower growth rate**
- ✓ **Elongated plasma structure due to anomalous perpendicular transports**

With self-electric fields (0D results)



✓ **Plasma T_e & n_e**

- Te drop (30 eV → 10 eV)
- Drastic decrease of n_e growth rate

✓ **Parallel heating**

- $E^{\parallel}_{self}$ cancels out $E^{\parallel}_{ext}$ ➡ ($E^{\parallel}_{tot}$ ⬇)
- Heating power is reduced

✓ **Transport**

- $v_e \parallel$ is reduced
- **Perpendicular transports** become dominant
- **Ion transport is greatly enhanced**

$$(v_e \perp \approx v_{H_2^+} \perp) > v_e \parallel \gg v_{H_2^+} \parallel$$

KSTAR Simulation Design

KSTAR reference breakdown scenario

- **Breakdown scenarios** are designed by considering **eddy currents** as a ring model and **ferromagnetic incoloy 908 material effect** as a non-linear model [6].

- Magnetic field configurations varies with time (0 - 60 ms)

- **Initial condition**

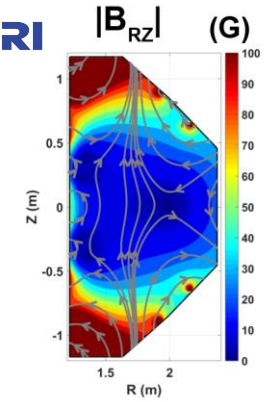
$$n_{\text{gas}} = 4 \times 10^{17}\ m^{-3}$$
$$n_{e0} = n_{i0} = 10^{6}\ m^{-3} \qquad T_{e0} = T_{i0} = 0.03\ \text{eV}$$

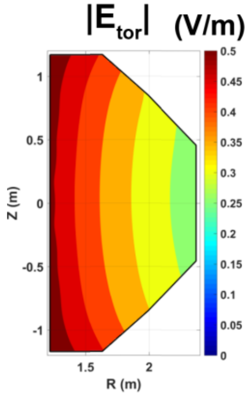
- **2 different simulations**

w/o self-electric fields ↔ **with self-electric fields**

difference

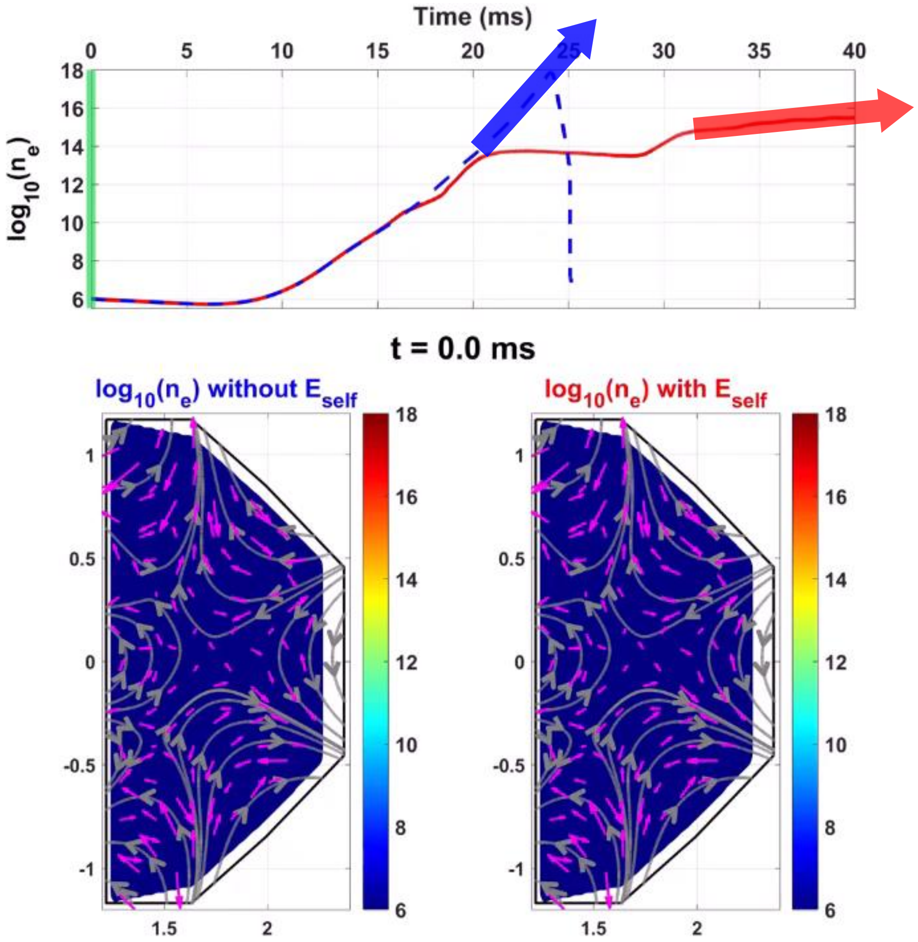
t = 30 ms





[6] Jayhyun Kim, *et al.*, Nucl. Fusion 51 083034 (2011)

BREAK simulation of KSTAR ohmic breakdown



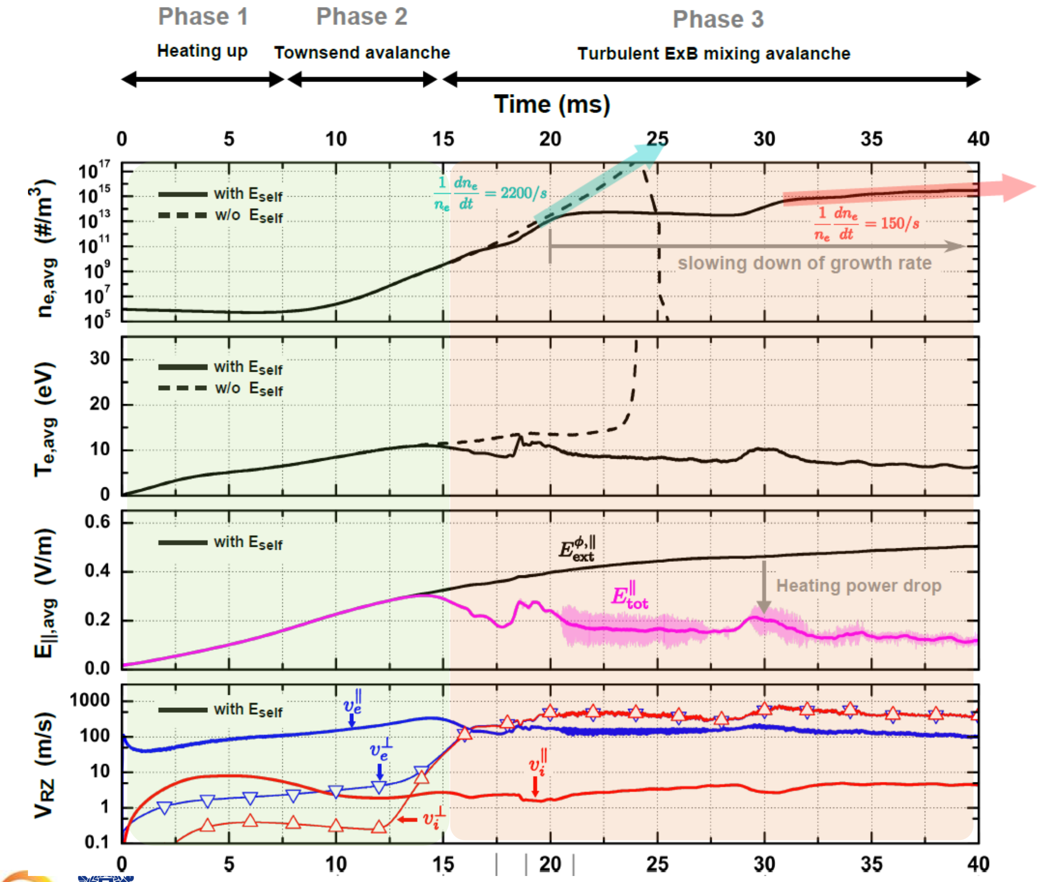
☐ without E_{self} (Townsend avalanche)

- Monotonic exponential growth
- Electron Parallel transport

☐ with E_{self} (Ohmic breakdown)

- Slowing down of growth rate
- Newly enhanced ExB transports

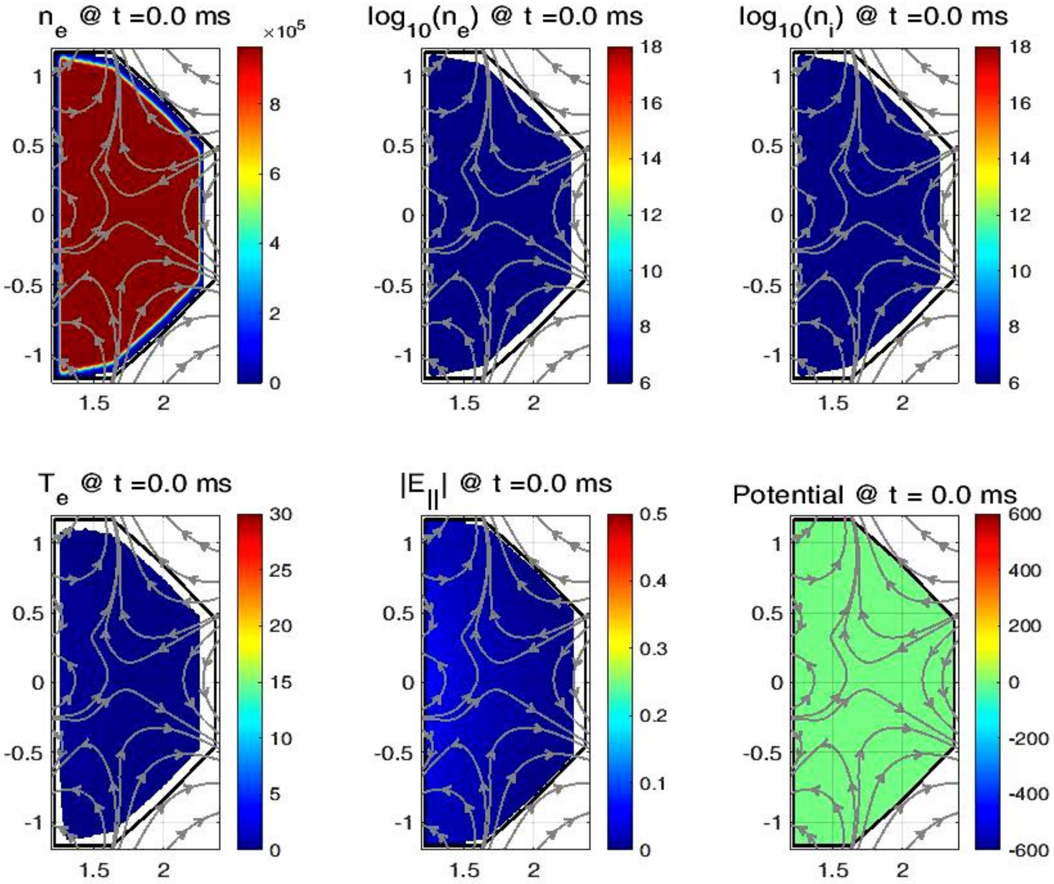
0D results of BREAK simulation



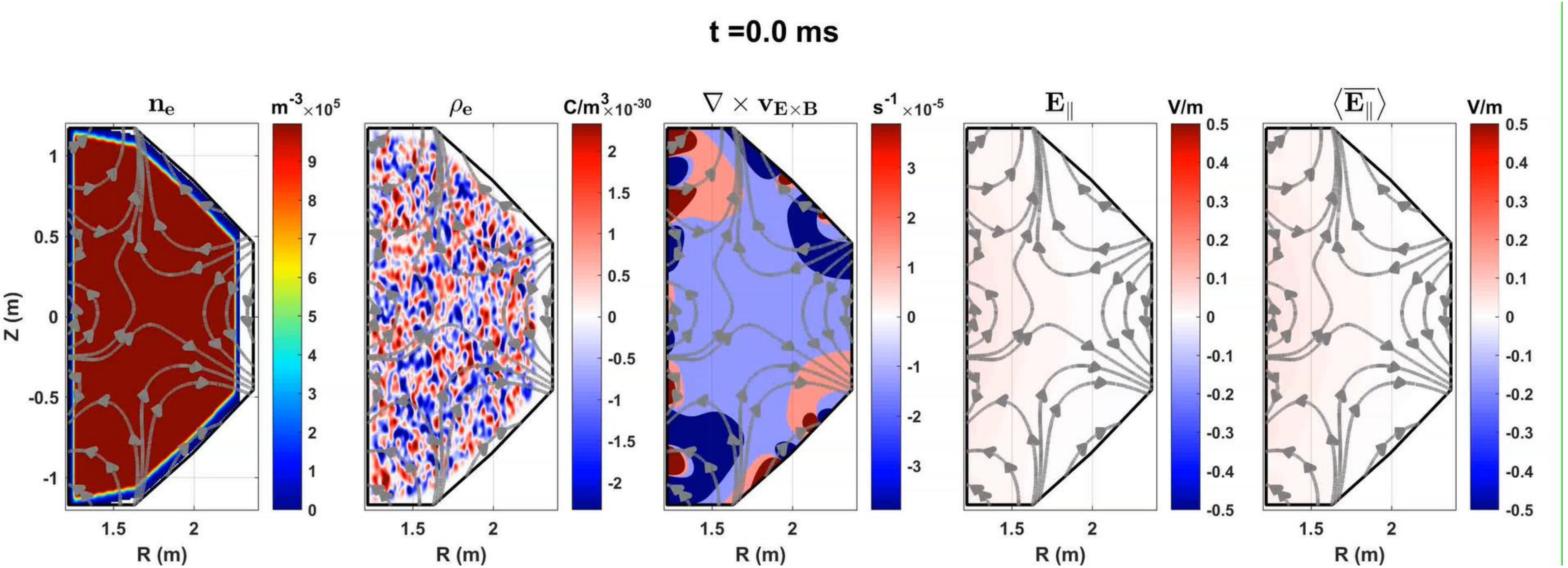
- **Plasma T_e & n_e**
  - Maintaining low Te (~ 10 eV)
  - Drastic decrease of n_e growth rate
- **Ohmic heating power drop**
  - $E^{\parallel}_{self}$ cancels out $E^{\parallel}_{ext}$ $(E^{\parallel}_{tot}$ ⬇ $)$
  - Heating power is reduced
- **Transports**
  - $v_e \parallel$ is reduced
  - Perpendicular transports by ExB
  - Ion transport is greatly enhanced

$$(v_e \perp \approx v_{H_2^+} \perp) > v_e \parallel \gg v_{H_2^+} \parallel$$

Temporal evolution of plasmas



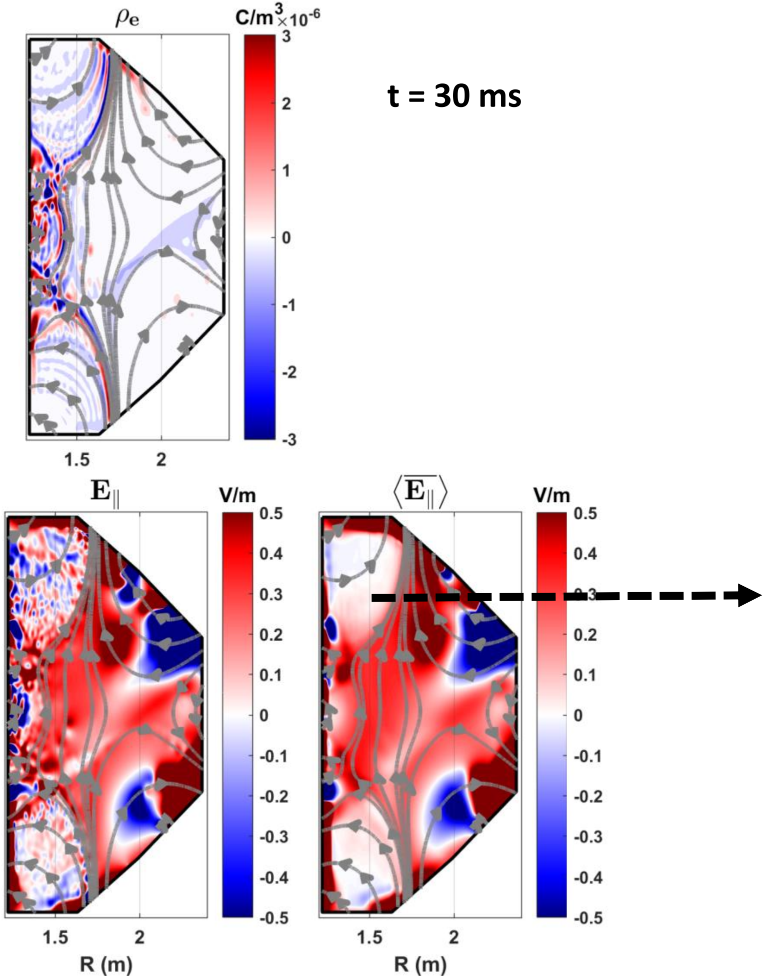
Turbulent plasma evolution during ohmic breakdown

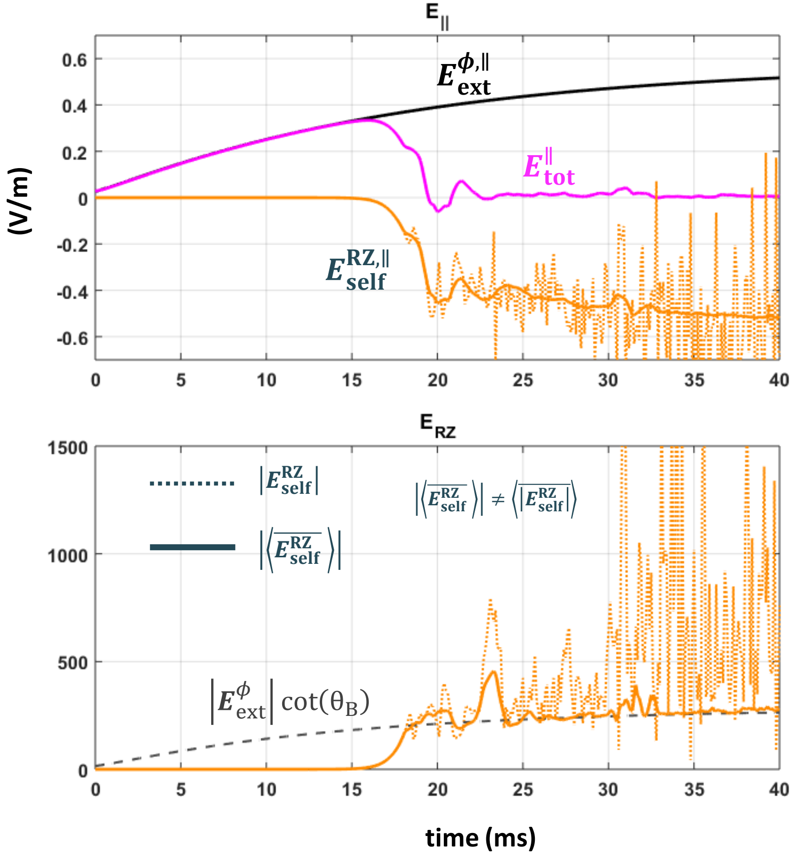


➔ The plasma evolution during the ohmic breakdown is very turbulent

Fluctuating and mean Self-electric field

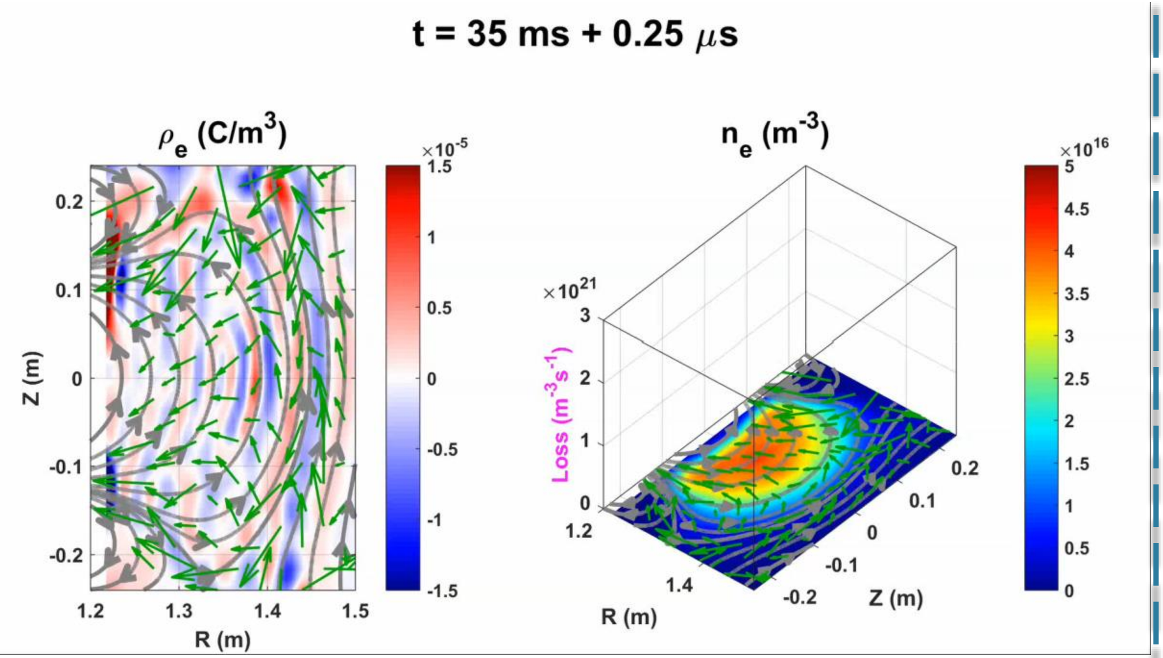
t = 30 ms





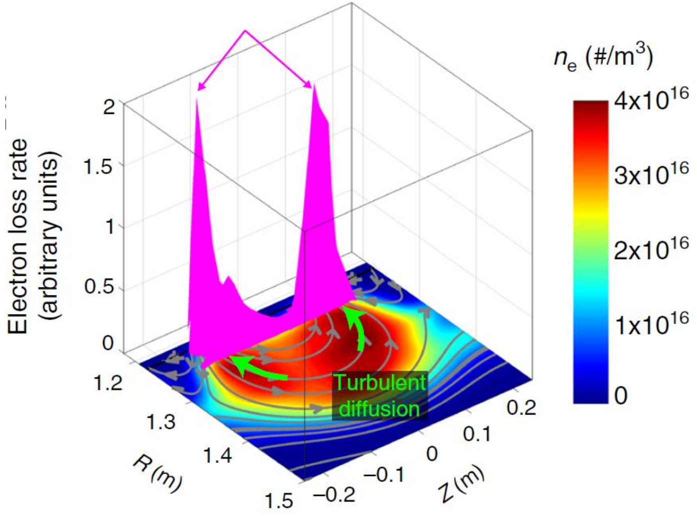
Turbulent ExB mixing and diffusion

In microseconds scale



t = 35 ms + 0.25 μs

In milliseconds scale



Turbulent ExB transports

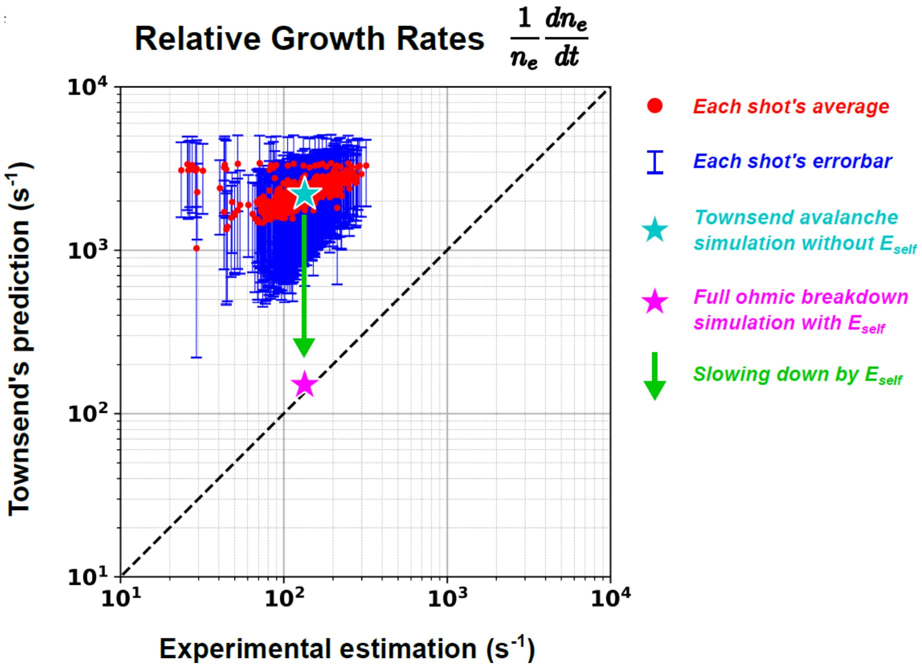
Faster diffusion along B_{RZ}

+

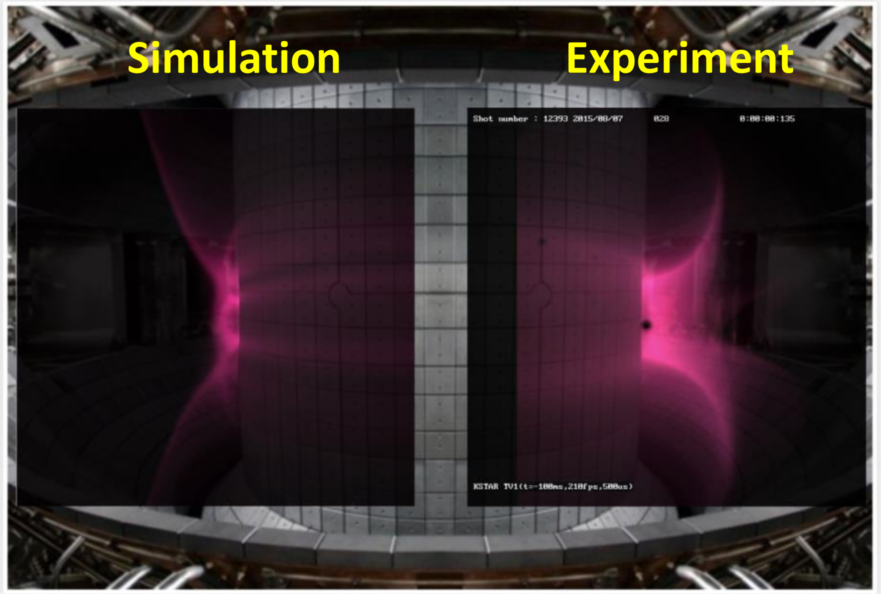
Slower mean ExB across B_{RZ}

Simulation results agree well with KSTAR experiments

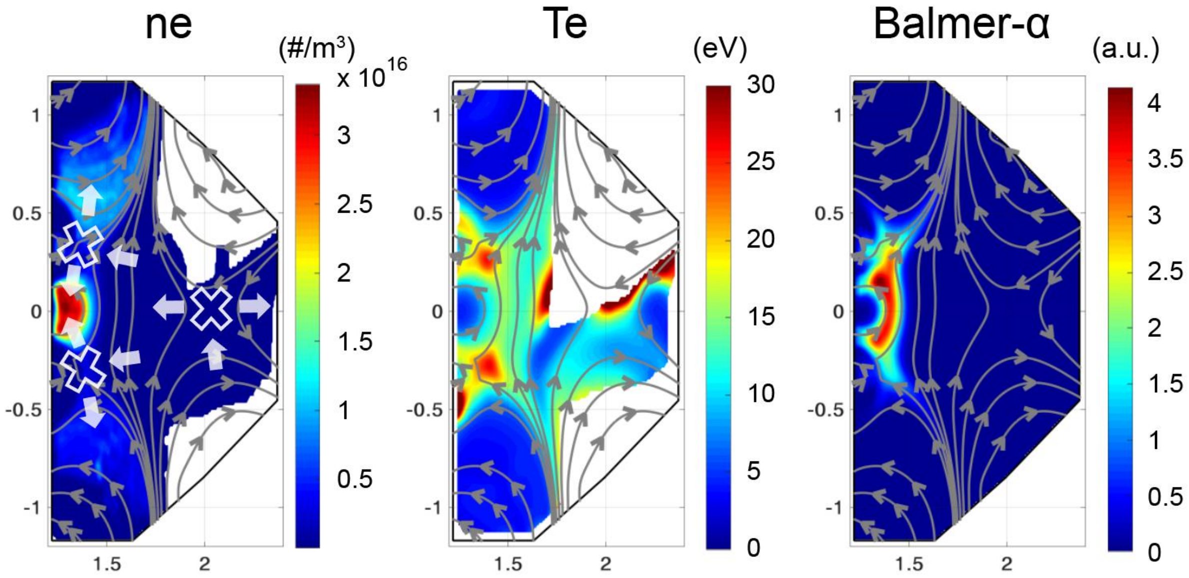
✓ Drastic decrease of growth rate



✓ Homogeneous plasma structure along B_{RZ}



Strongly Inhomogeneous Plasma Evolution



- **How to understand the strongly inhomogeneous plasma evolution in the complex EM topology?**
- **Is it possible to predict the overall plasma structures & behaviors?**

Previous understanding of X-point topology

- **Characteristics of X-point region**
  - Infinitesimal pitch angle

$$|B_{RZ}| \approx 0,\ \theta_B \approx 0$$

  - Long connection length

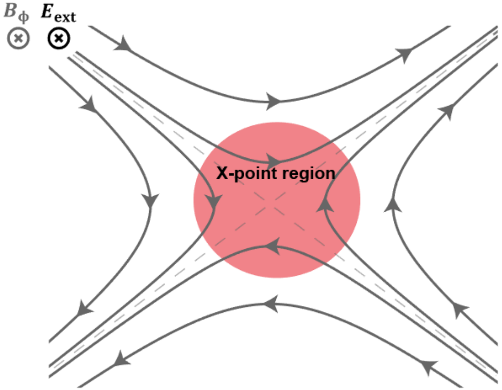
$$L_c \sim a_X\ |B_{tor}|/|B_{RZ}| \gg 1$$

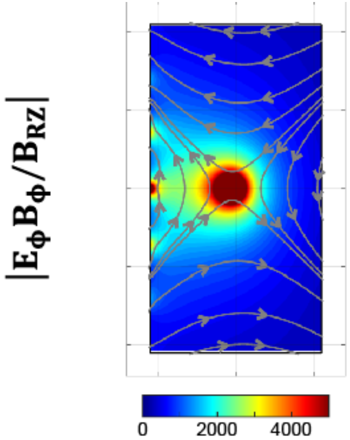
  - Long confinement time

$$\tau_{\parallel} \sim L_c/v_{e,\parallel}$$

- **Empiricial condition to determine plasma position**

$$\left|\frac{E_\phi B_\phi}{B_{RZ}}\right| > 1000\ \mathrm{V/m}$$

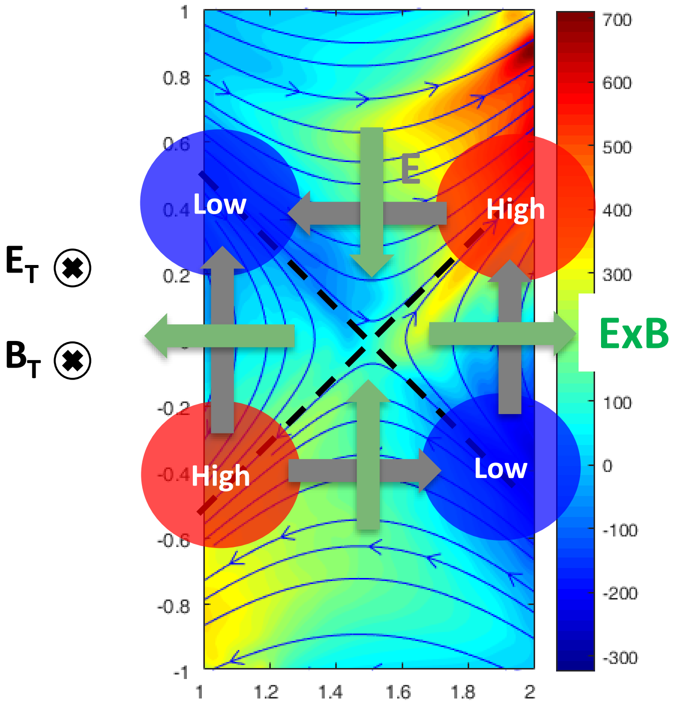




How does the self-electric field come into play regarding the X-point topology?

Potential structure around the X-point

Potential structure



- Required self-electric fields to cancel the external fields

$$\left\langle \overline{\mathbf{E}_{\text{self}}^{RZ}} \right\rangle = \left|\mathbf{E}_{\text{ext}}^{\phi}\right| \cot\theta_B \left(-\widehat{\mathbf{E}}_{\text{ext}}^{\phi}\cdot\widehat{\mathbf{B}}_{\phi}\right)\widehat{\mathbf{B}}_{RZ}$$

- ExB drifts induced by the self-electric fields

$$\left\langle \overline{\mathbf{v}_{E\times B}^{RZ}}\right\rangle = \frac{\left\langle \overline{\mathbf{E}_{\text{self}}^{RZ}}\right\rangle \times \widehat{\mathbf{B}}_{\phi}}{B} = \frac{\left|\mathbf{E}_{\text{ext}}^{\phi}\right|}{\left|\mathbf{B}_{RZ}\right|}\cos\theta_B\left(\widehat{\mathbf{E}}_{\text{ext}}^{\phi}\times\widehat{\mathbf{B}}_{RZ}\right)$$

Comprehensive understanding of X-point topology

Critical plasma densities at X-point region

- $\theta_B \rightarrow 0$
- $n_{\mathrm{crit},\parallel} \propto \cot^2(\theta_B) \rightarrow \infty$
- $n_{\mathrm{crit},\perp} \propto \tan^2(\theta_B) \rightarrow 0$

Parallel dynamics

- **Higher heating at X-point region**

  $n \ll (n_{\mathrm{crit},\parallel} \approx \infty)$

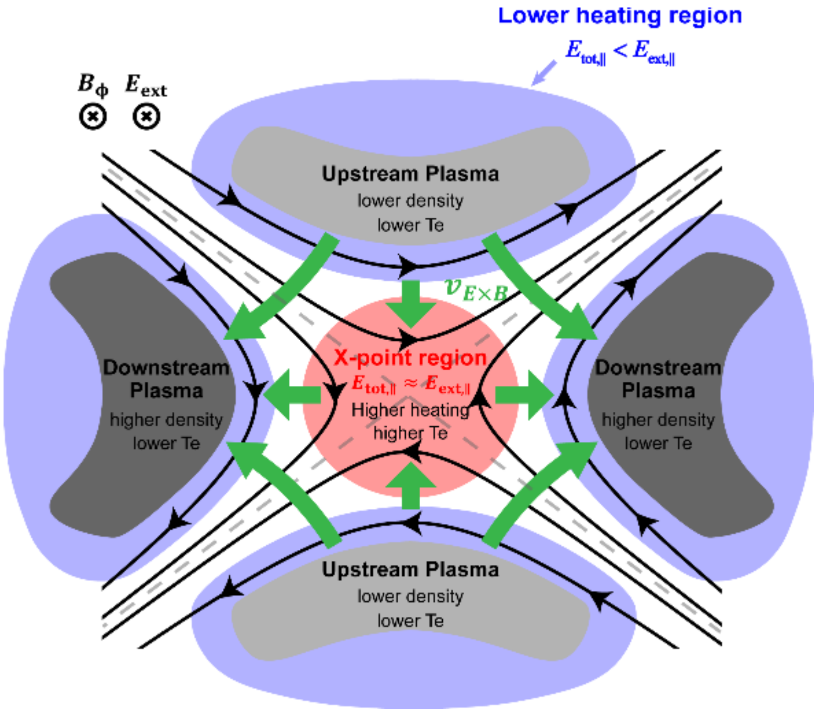
- **Lower heating at other regions**

  $n > n_{\mathrm{crit},\parallel}$

Perpendicular dynamics

- **Two inflows + Two outflows by mean ExB**

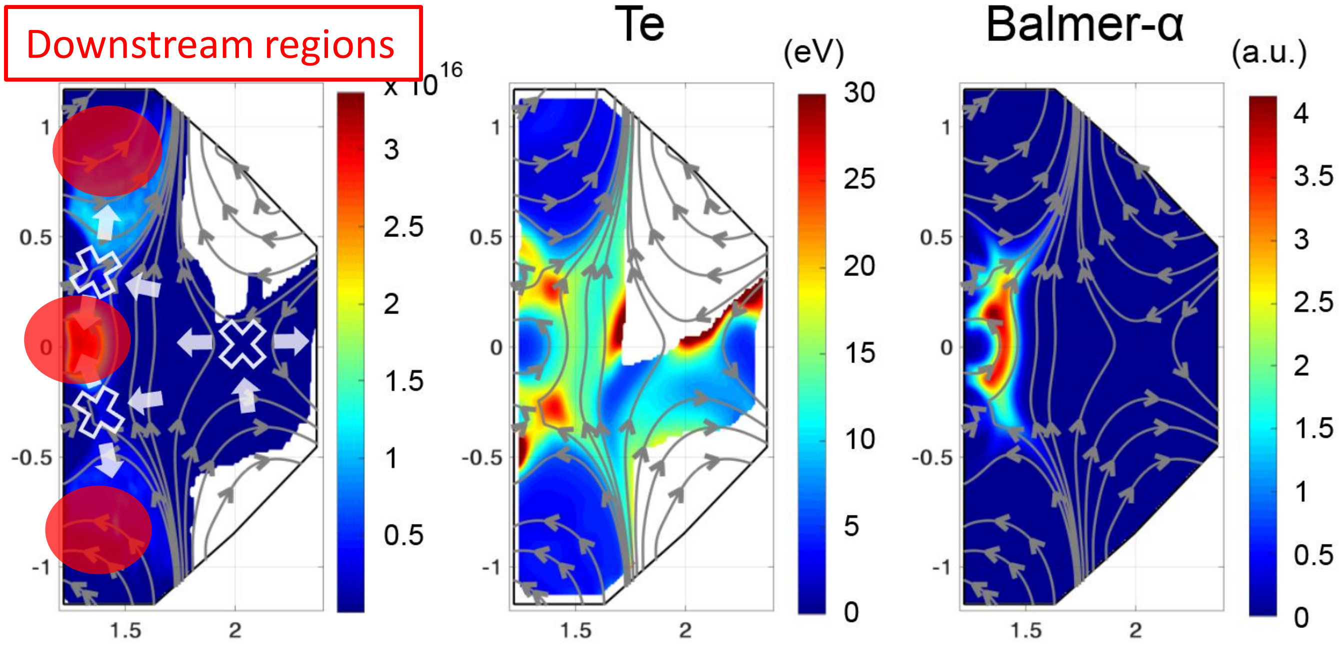
  $n > n_{\mathrm{crit},\perp}$



→ Topology analysis on external EM fields predicts overall plasma evolution

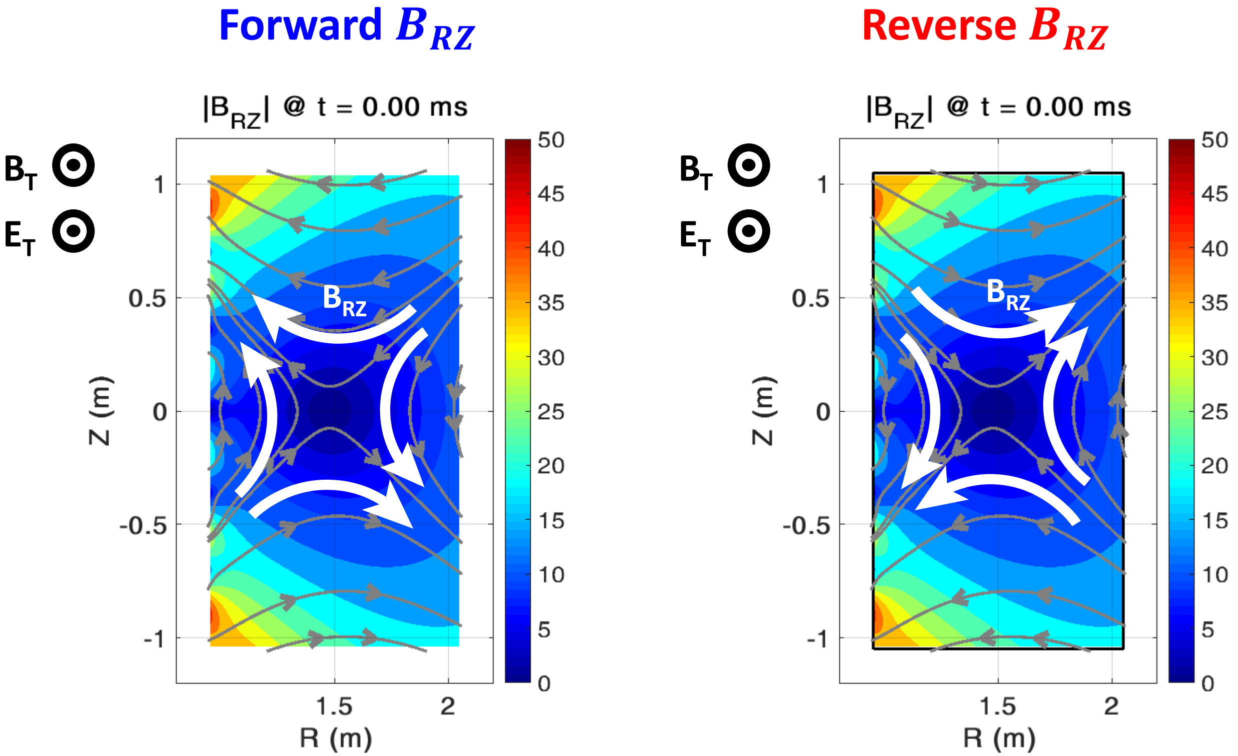
→ Plasma density would be higher at downstream region

Interpretation of KSTAR simulation results



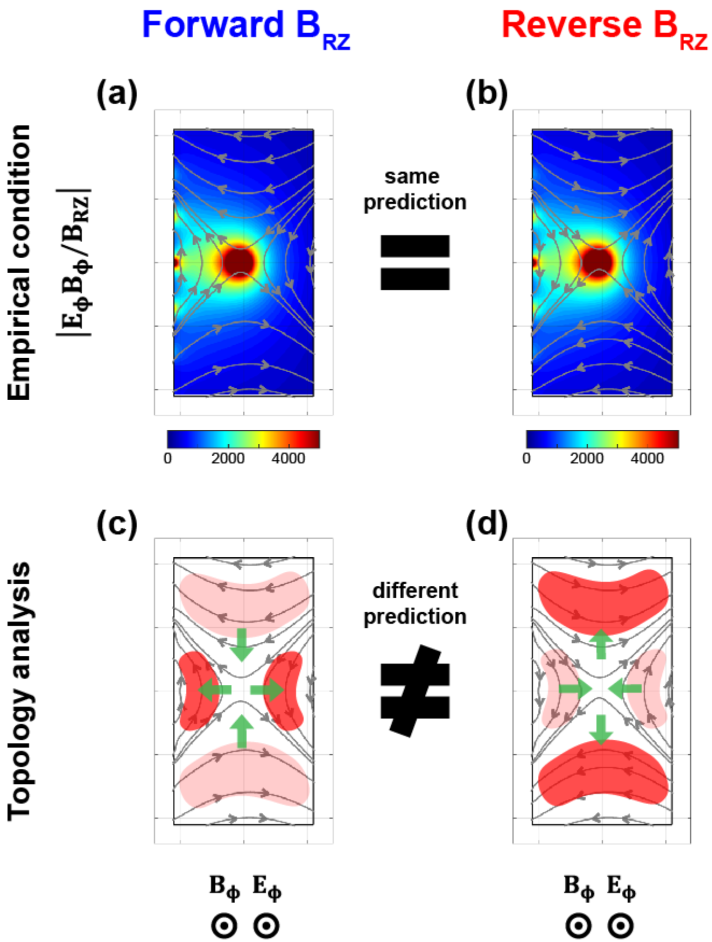
- **Plasma densities** are higher at **downstream regions**
- **Plasma temperatures** are higher at **X-point regions**
- **Balmer line emissions are observed at higher temperature regions**

New physical insights on scenario design strategy



Same magnitudes, but opposite direction of B_{RZ}

New physical insights on scenario design strategy



✓ (Previous) **Empirical condition**

- Same prediction for 2 cases
- High plasma density at X-point region

✓ (New) **Topology analysis method**

➡ Predicted mean ExB

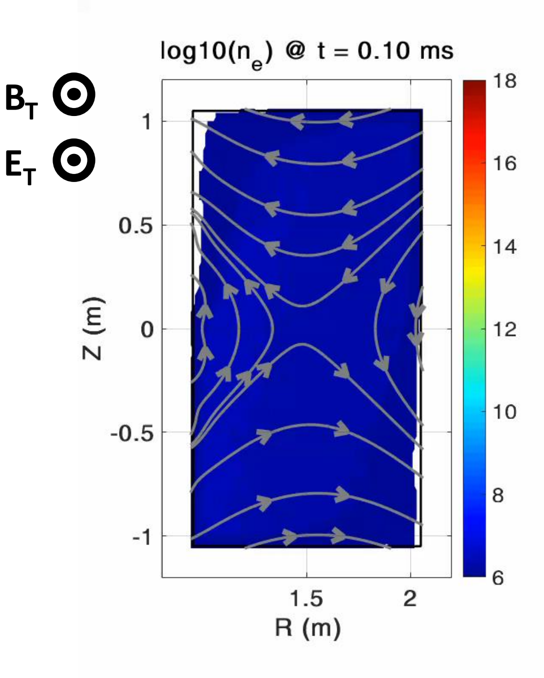
▨ Upstream region
Low plasma density

🟥 Downstream region
High plasma density

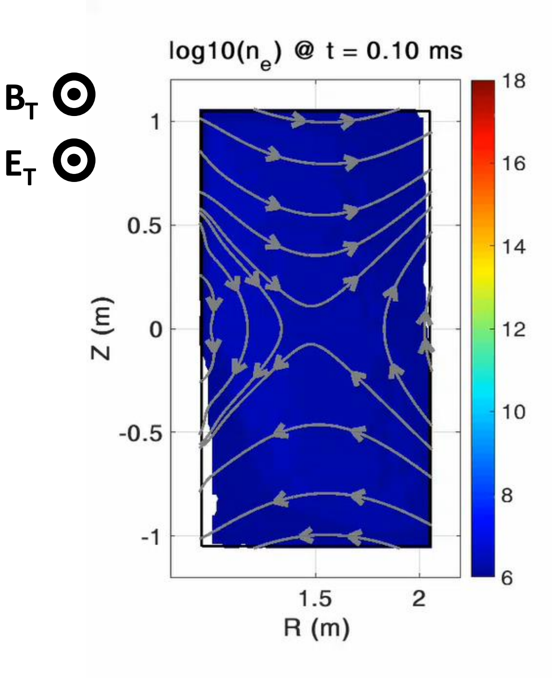
- Different prediction for 2 cases
- High plasma density at downstream region

New physical insights on scenario design strategy

Forward B_{RZ}



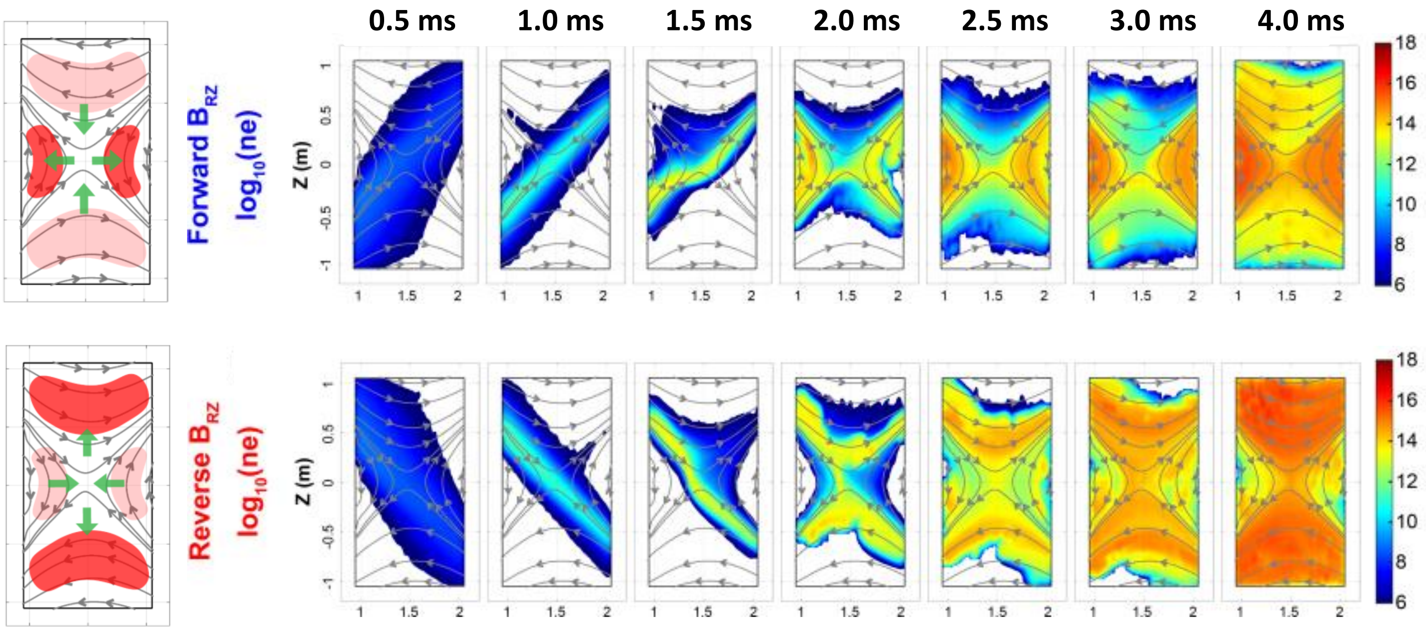
Reverse B_{RZ}



➡ **Topology analysis method well predicted the plasma behaviors**

New physical insights on scenario design strategy

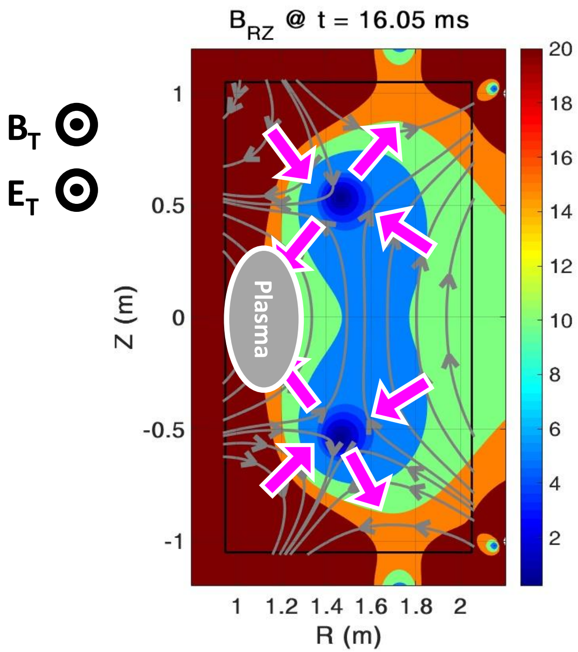
Topology analysis



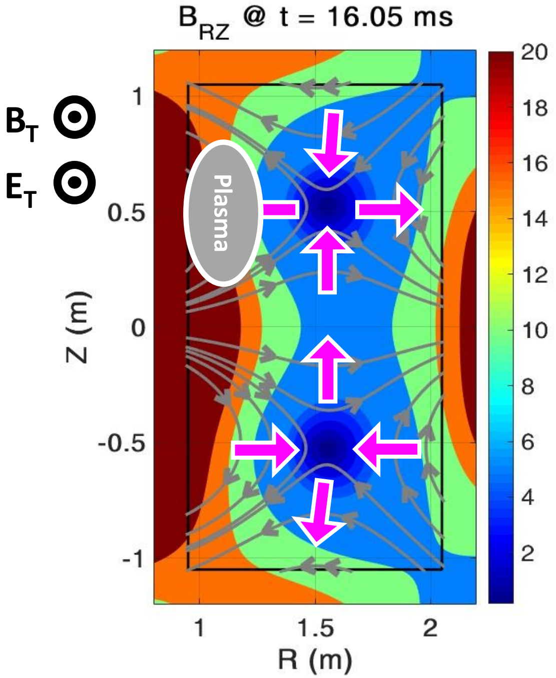
➡ **Topology analysis method well predicted the plasma behaviors**

New physical insights on scenario design strategy

Artificial Double Null case 1



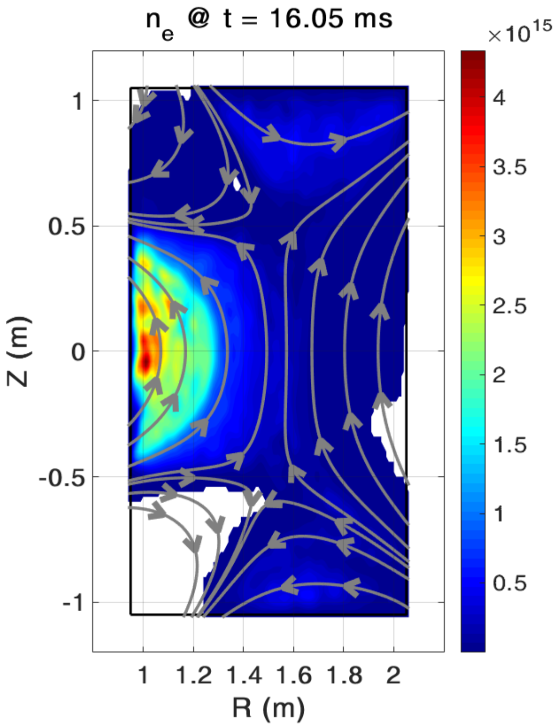
Artificial Double Null case 2



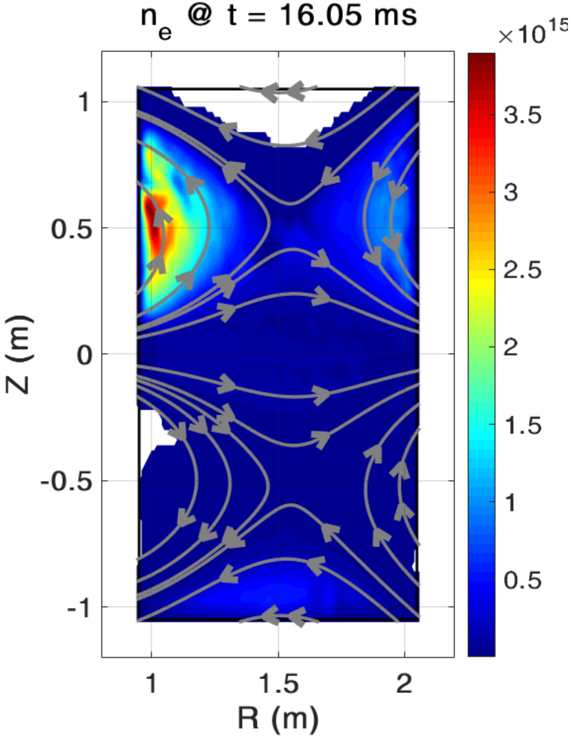
➡ **Plasma behaviors and positions could be predicted by topology analysis**

New physical insights on scenario design strategy

Artificial Double Null case 1



Artificial Double Null case 2



- **Topology analysis method well predicted the plasma behaviors**
- **Plasma position could be controlled by designing of X-point topology**

Summary

- We propose the **first systematic breakdown theory** by considering **plasma response** : **"Turbulent ExB mixing avalanche"**

M.-G. Yoo, *Nat. Commun.* (2018) 9:3523

- **Crucial roles of self-electric fields** as the plasma response are newly discovered
  - ✓ **Cancellation of external electric fields** **(parallel)**
    - Heating power and growth rate decrease
    - Responsible for slow plasma formation
  - ✓ **Dominant new transport by ExB drifts** **(perpendicular)**
    - Dominant transport mechanism especially for heavier ions
    - Responsible for homogeneous plasma structure along magnetic field lines

- The new physical insights on the complex EM topology can help designing robust breakdown scenario strategy

- The theory is getting paid attention in start-up researches
  - D.J. Battaglia, *et al.*, "Reduced model for direct induction startup scenario development on MAST-U and NSTX-U" Nucl. Fusion **59** (2019)