PPPL Associate Research Physicist

Postdoctoral interview

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Understanding mechanisms underlying ohmic breakdown in a tokamak by considering multi-dimensional plasma responses

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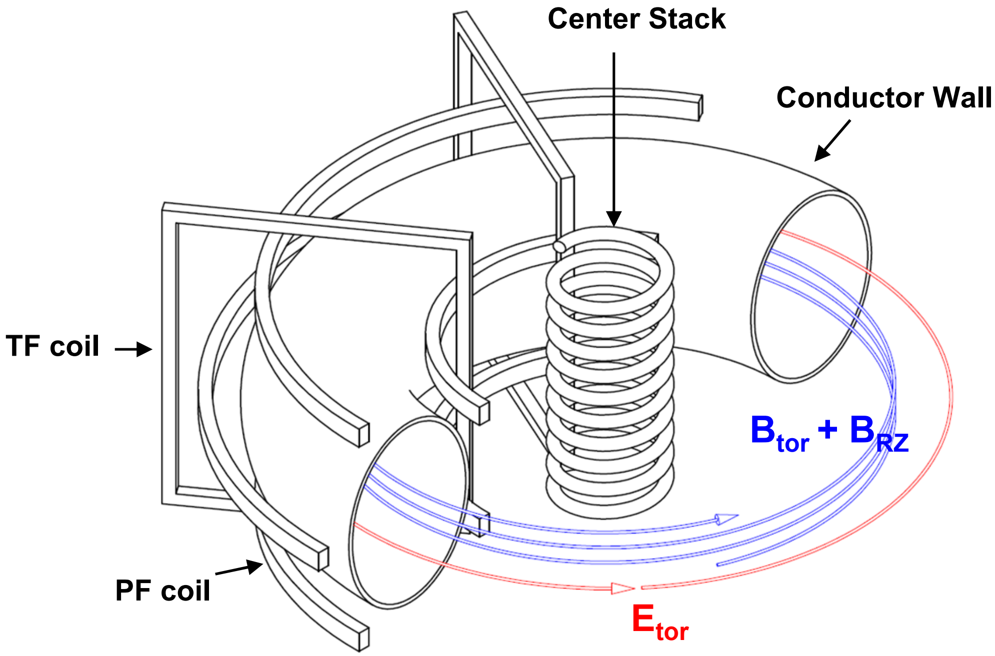
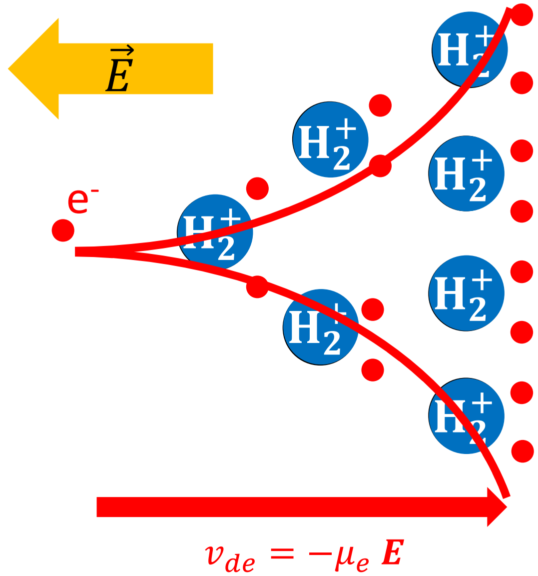
Introduction
What is the ohmic breakdown?





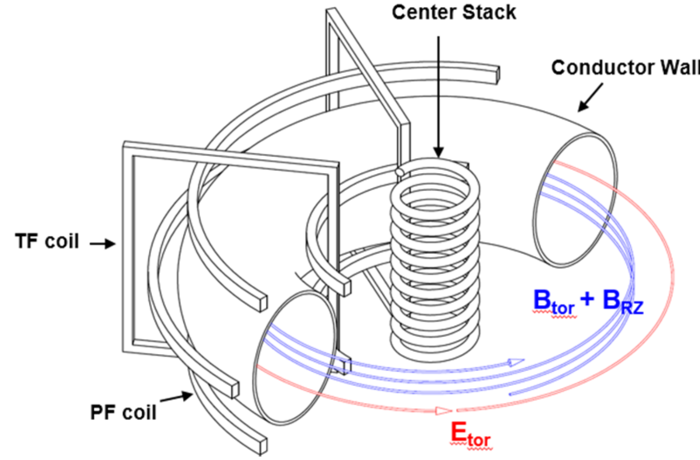
Electron avalanche

- **Ohmic breakdown is a first operation phase in tokamak to produce initial plasmas**
- **Plasma density increases exponentially due to the electron avalanche**
- **Limited toroidal electric field ($\mathbf{E_{tor} \leq 0.3\ V/m}$) in ITER due to operation limit**

Introduction
Distinct characteristics of Ohmic breakdown

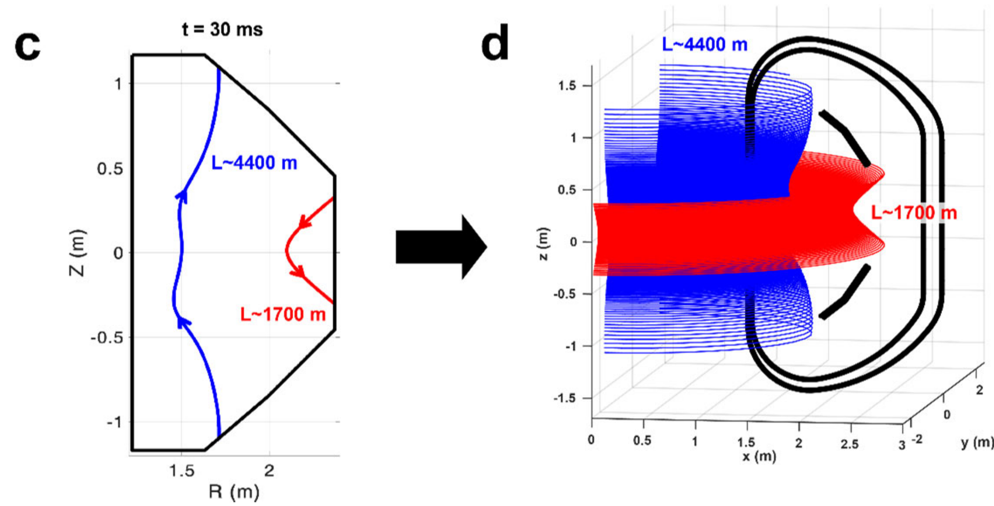
✓ **Open magnetic field lines**

- External magnetic fields are dominant
- Plasma current is negligible



✓ **Low pitch angle**

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



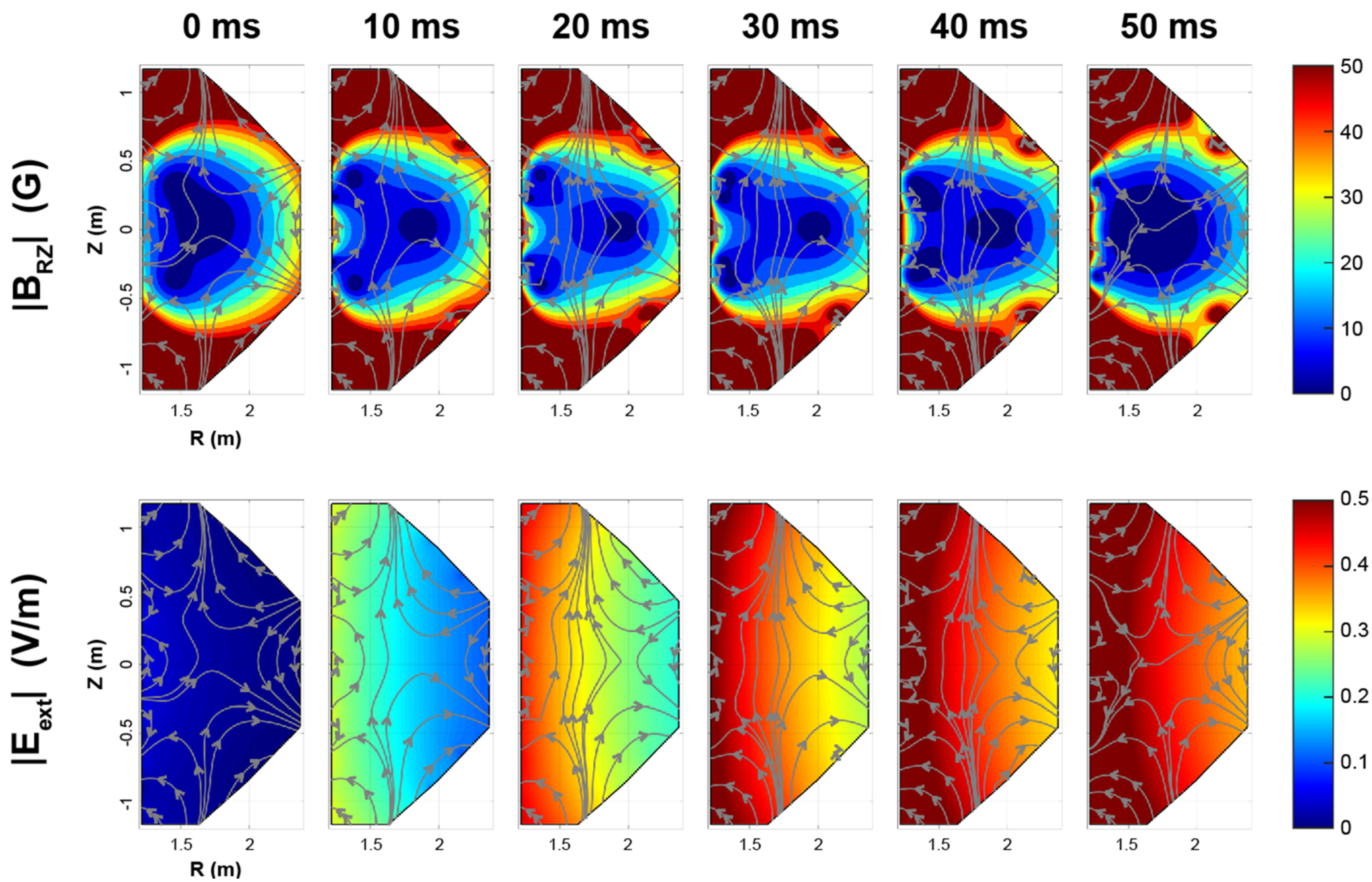
✓ **Toroidal electric fields**

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

➡ **Underlying physical mechanism of the breakdown have been obscured over 50 years**

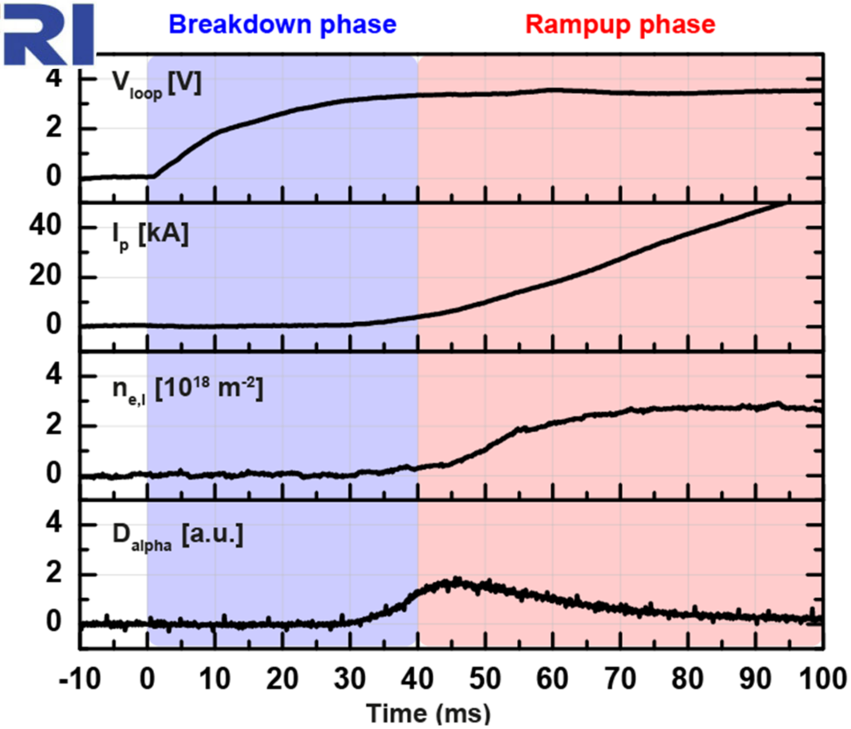
Introduction
Time-varying complex electromagnetic fields

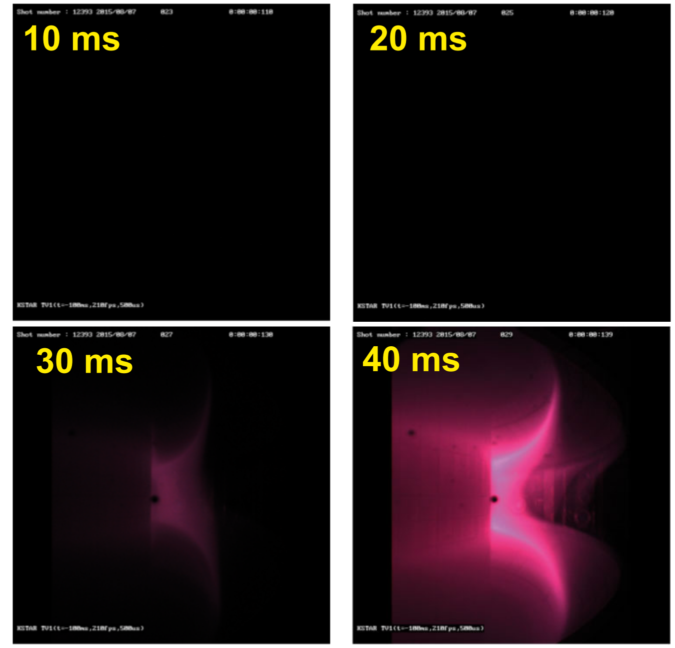
- (time-varying) CS currents + PF currents + eddy currents



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

Introduction
Lack of experimental observations





Initial plasma during breakdown

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

⟷

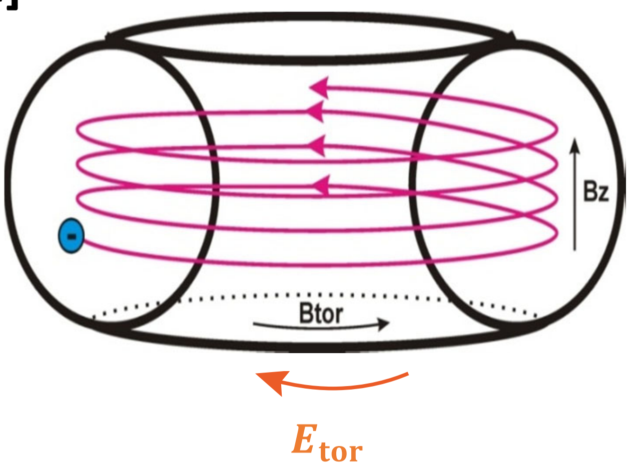
Target plasma of usual diagnostics

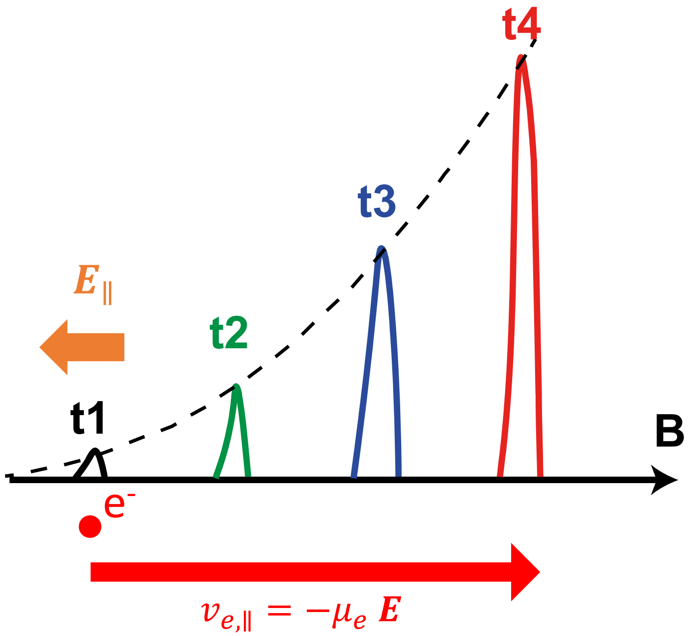
- **Hot** (> 100 eV)
- **Dense** (> 10^{18} m^{-3})

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

Adopting simplest theory: Townsend avalanche theory

[1]





1. Electrons move following the magnetic field lines (parallel transport dominance)

$$v_{e,\parallel} = -\mu_e \boldsymbol{E} \qquad v_{e,\parallel} \gg v_{e,\perp}$$

2. Electron density increases exponentially (Townsend avalanche[2])

$$n(x) = n_0 \exp(\alpha x_{\parallel})$$

$$\alpha = Ap \exp(-Bp/\boldsymbol{E}_{\mathrm{ext},\parallel})$$

Assumption

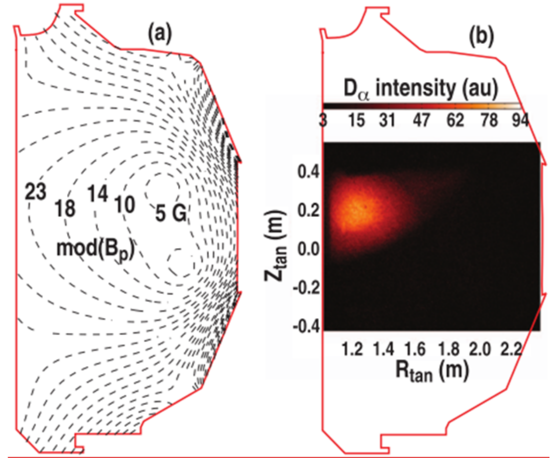
External electric fields are dominant

[1] Jan Stockel, "Plasma start-up in tokamaks", Winter School, Marianska, January 21, 2010
[2] J. S. Townsend : Electrons in Gases. Hutchinson's Scientific and Technical Publications. London 1948.

Previous works
Field quality analyses of external EM structure

Based on the Townsend avalanche theory… [6]

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



Field quality analysis

0D effective parameters [4]	**Empirical condition** [5]	**2D field-line-integration** [6,7]
$L_{\text{eff}} \cong 0.25\, a_{\text{eff}} B_T/B_p$	$E_T B_T/B_\perp > 1000\ \text{V/m}$	$L = \int_{\vec{B}} dl \qquad V = \int_{\vec{B}} \vec{E}\cdot d\vec{l}$

Limitations

- Static field analysis at a specific time ➔ **No dynamic plasma evolution (ne, Te)**
- **Self-electric fields** are ignored ➔ **No plasma response**

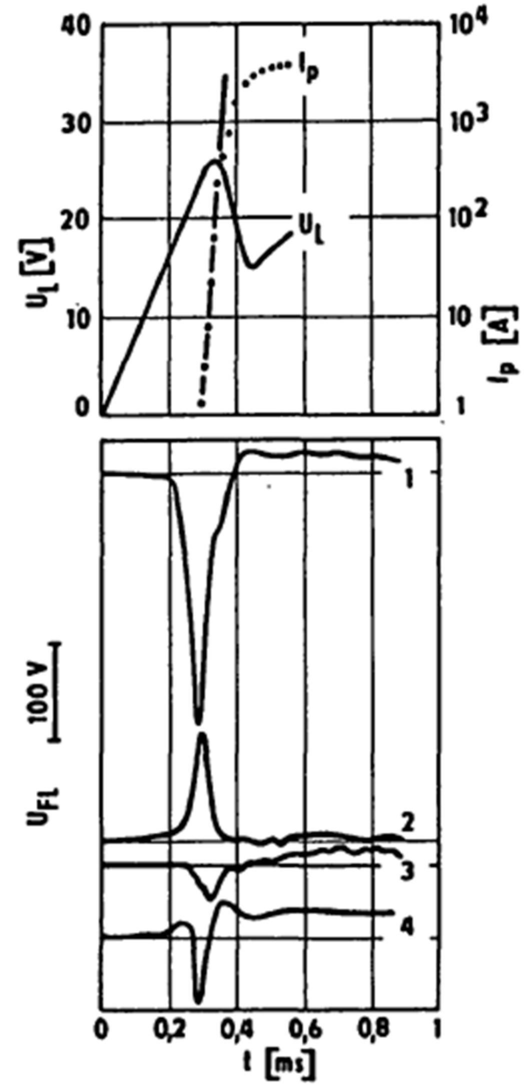
[4] R. Yoshino, *et al.*, Plasma Phys. Control. Fusion **39** 205 (1997)
[5] Tanga, A., in Tokamak Start-up (ed. U. Knoepfel), Plenum Press, New York 159 (1986)
[6] Lazarus E.A., *et al.,* Nucl. Fusion **38** 1083 (1998)
[7] G.L. Jackson, *et al.*, POP **17** 056116 (2010)

Motivation

Existence of strong self-electric fields in tokamak

- **The existence of strong self-electric fields (~kV/m) in RZ plane was measured in CASTOR tokamak 30 years ago [3]**

M. Valovic, NF (1987)



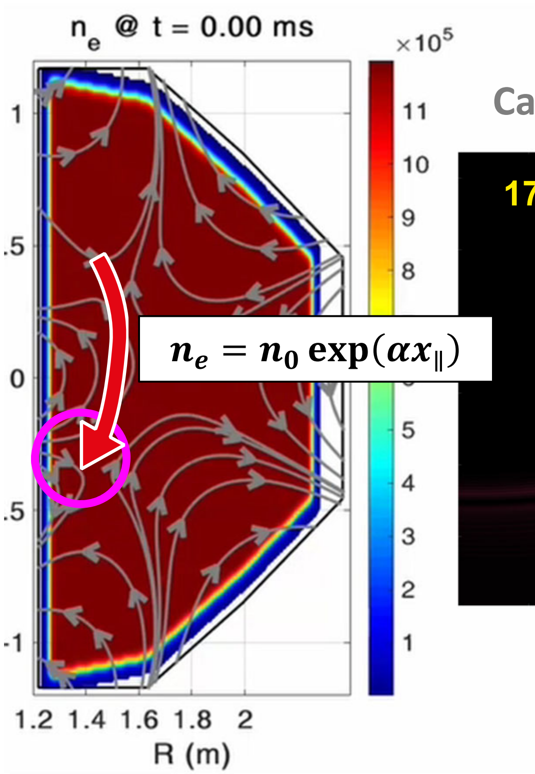
- **CASTOR tokamak (R_0 = 0.4 m, a = 85 mm)**
- **Convection loss by ExB drifts 2-3 orders of magnitude larger than Bohm diffusion**

➡ **Roles of self-electric fields have been still shrouded in mystery due to complex EM topology**

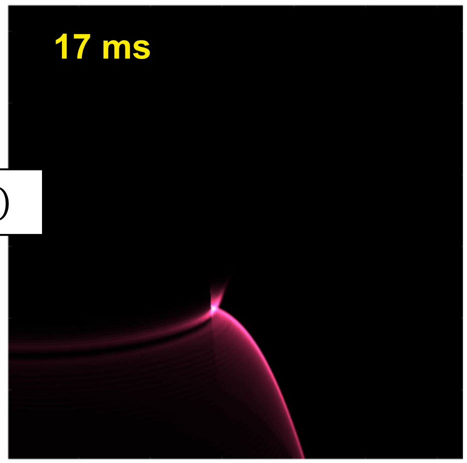
[3] M. Valovic, Nucl. Fusion **27** 599 (1987)

Motivation
Mysterious experimental results

Townsend avalanche simulation

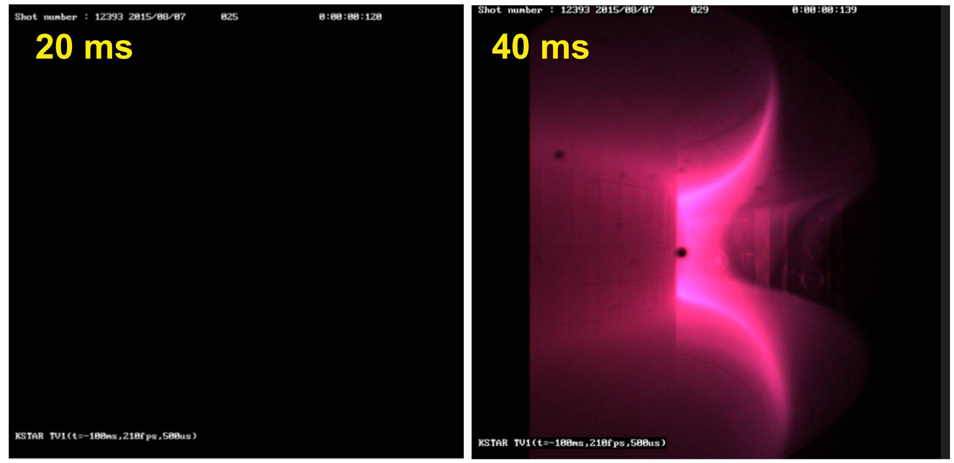


Calculated Hα image



Visible camera from Experiment

Observed Hα image



1. Fast avalanche

2. Localized & asymmetric structure

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

≠

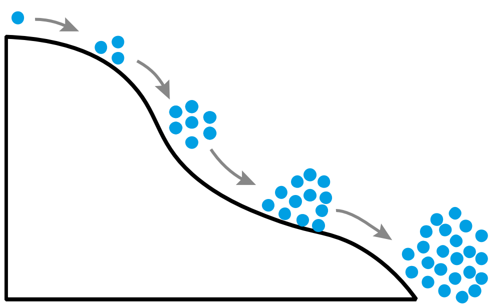
1. Much slower avalanche

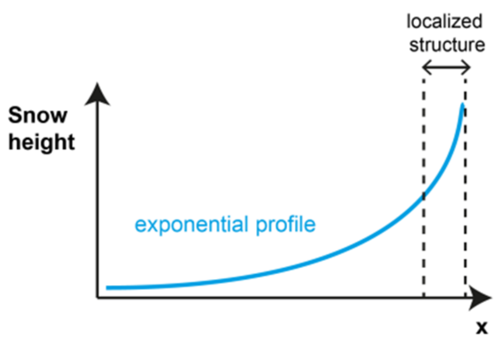
2. Elongated & symmetric structure

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

Mysterious experimental result
Homogeneous plasma structure along magnetic field line

Townsend avalanche
(Snow avalanche)





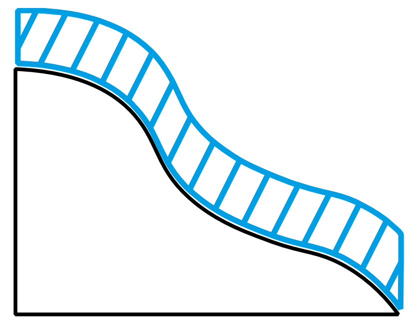
✓ **Exponential profile**

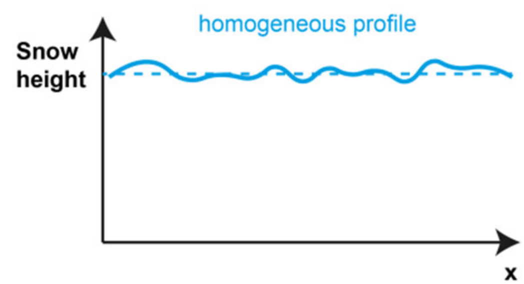
$$n(x_{\text{slope}}) = n_0 \exp(\alpha x_{\text{slope}})$$

Snowball = Electrons
Gravity = Toroidal E fields
Slope = B field lines

≠

Actual avalanche in tokamak





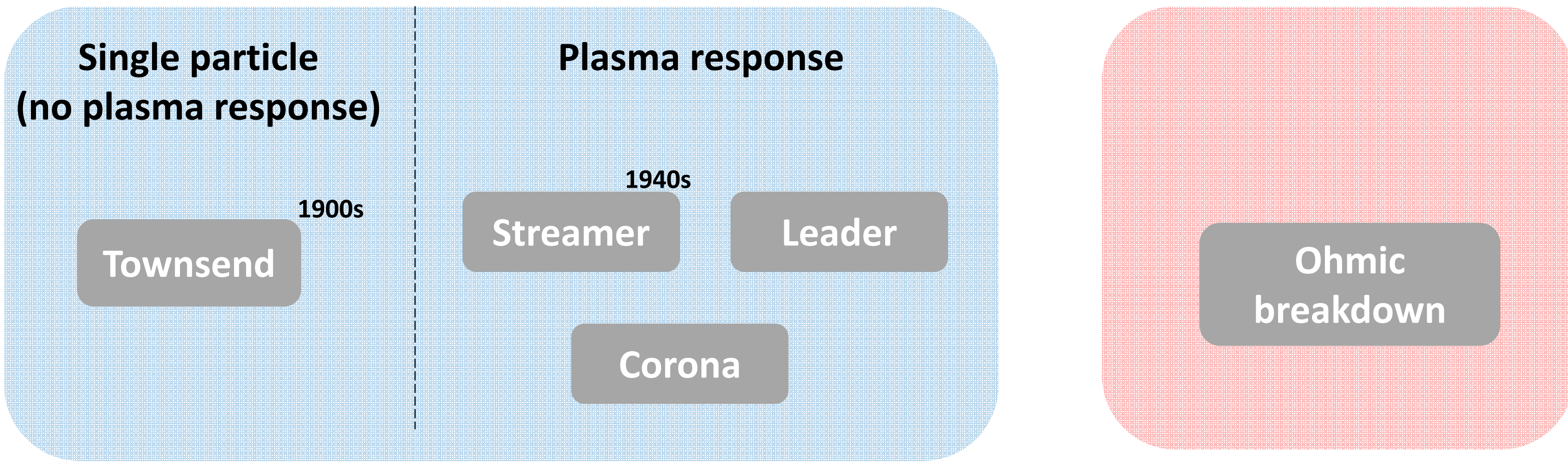
✓ **Homogeneous profile**

$$n(x_{\text{slope}}) \approx M \times n_0$$

➡ **Townsend theory cannot explain the avalanche phenomena in tokamak**

Brief history of gas breakdown theory

Unmagnetized system | **Strongly magnetized system**



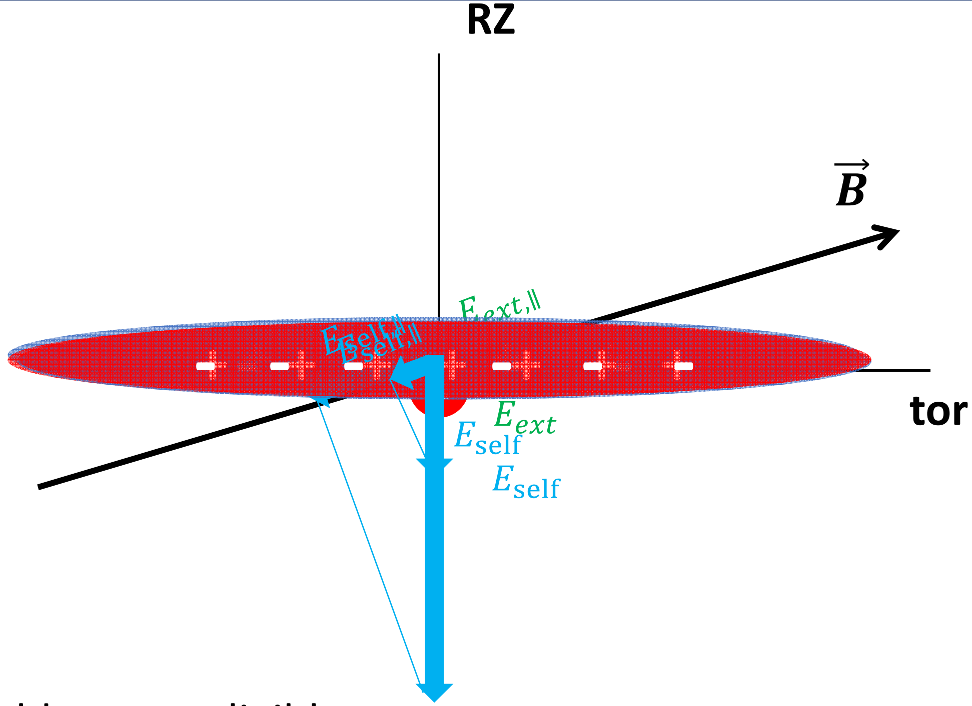
A new type of breakdown theory is required for the strongly magnetized system by considering…

- ✓ The nature of gyromotion and guiding center motion
- ✓ The roles of self-electric fields regarding strong magnetic fields

Toroidally symmetric plasma model
Roles of self-electric fields

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

self-electric fields (↑ ∇V)



- $n \ll n_c$ (low density)

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

- $n \gtrsim n_c$ (high density)

  $|\boldsymbol{E}_{\mathbf{self},\parallel}| \sim |\boldsymbol{E}_{\mathbf{ext},\parallel}|$ ⇒ Total electric fields is reduced $(E_{\mathrm{tot},\parallel} = E_{\mathrm{ext},\parallel} + E_{\mathrm{self},\parallel} \rightarrow 0)$

  $|\boldsymbol{E}_{\mathbf{self},\perp}| \gg |\boldsymbol{E}_{\mathbf{ext},\perp}|$ ⇒ $\vec{E} \times \vec{B}$ drift motions

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

Toroidally symmetric plasma model
Roles of self-electric fields

Plasma Density

Parallel dynamics

Slow avalanche

Reduced heating

Reduced parallel transport

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

($10^{12} \sim 10^{14}$ m^{-3})

Fast avalanche

Dominant parallel transport

Perpendicular dynamics

Dominant perp. transport via ExB drift

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

($10^{12} \sim 10^{14}$ m^{-3})

Negligible perp. transport

New regime due to plasma responses

Townsend avalanche

Toroidally symmetric plasma model
Parallel dynamics

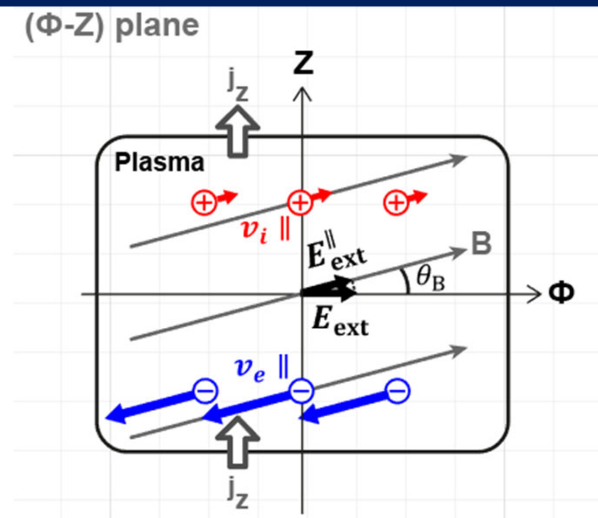
- **Separation force ($E_{\text{ext}}^{\phi,\parallel}$)   vs.   Attracting force ($E_{\text{self}}^{RZ,\parallel}$)**

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

- **Equilibrium state in parallel direction**

$$E_{\text{ext}}^{\phi,\parallel} = -E_{\text{self}}^{\text{RZ},\parallel} \;\Rightarrow\; \left|\overline{\boldsymbol{E}_{\text{self}}^{\text{RZ}}}\right| = \left|\boldsymbol{E}_{\text{ext}}^{\phi}\right| \cot(\theta_{\text{B}}) \gg \left|\boldsymbol{E}_{\text{ext}}^{\phi}\right|$$

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



Parallel critical density

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

- **Cancellation of external electric fields**

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

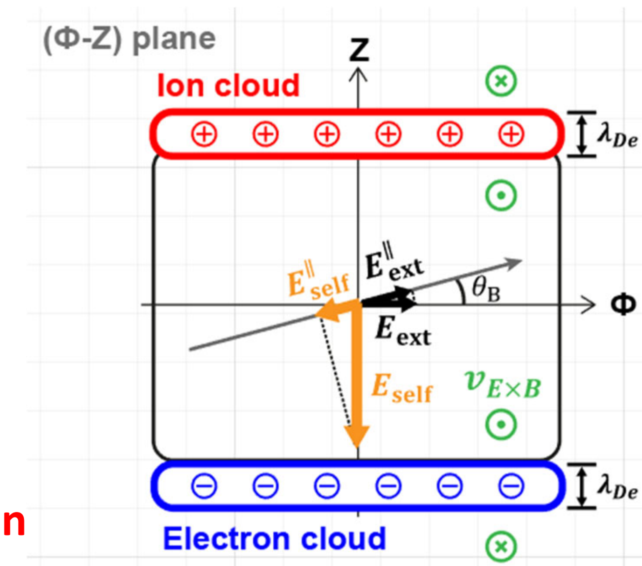
Parallel transport ⬇

Heating power ⬇

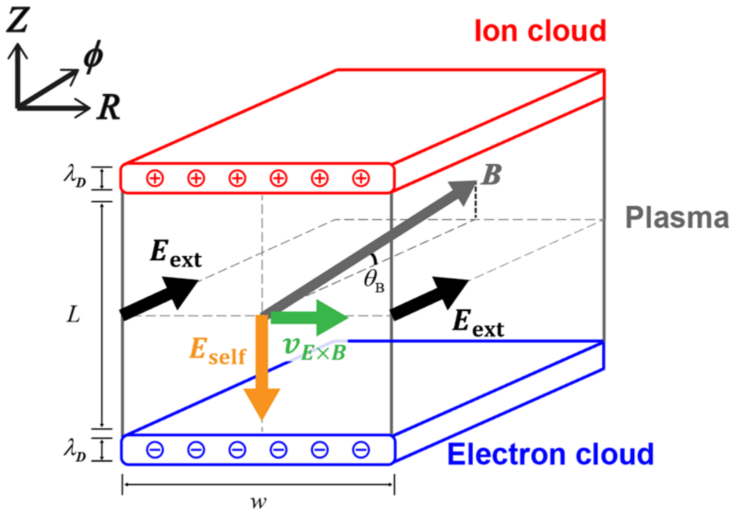
Electron temperature ⬇

Avalanche growth rate ⬇

➡ **Key mechanism for mysterious slow plasma formation**

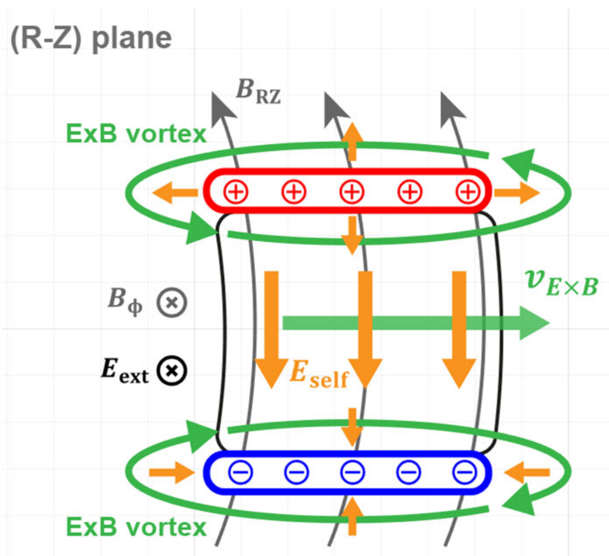


Toroidally symmetric plasma model
Perpendicular dynamics



✓ **Mean ExB across B_{RZ}**

- ➔ Induced by spatial-temporal average $\overline{E_{\text{self}}^{\text{RZ}}}$
- ➔ Determine overall plasma flow and position
- ➔ Dominant convective loss term
- ➔ Perpendicular confinement time of the plasma ($\tau_\perp = a/v_{E\times B}$)



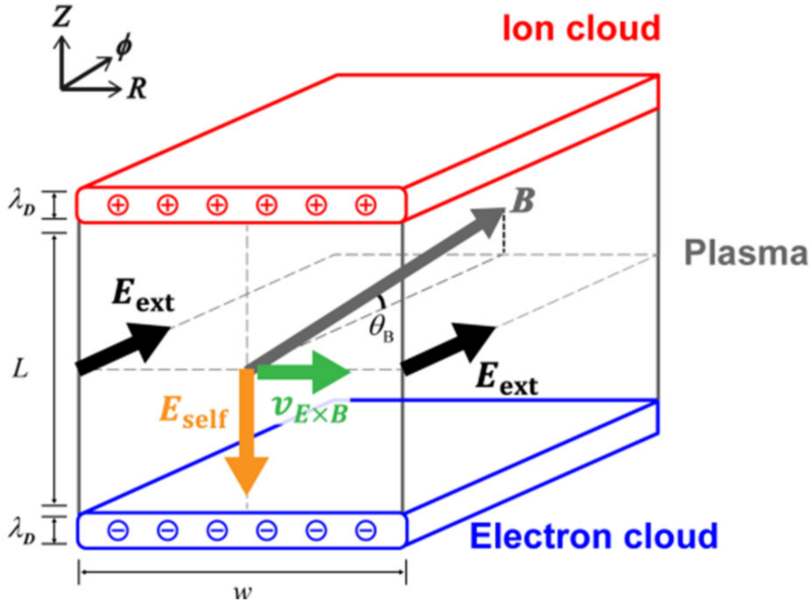
✓ **Turbulent ExB mixing along B_{RZ}**

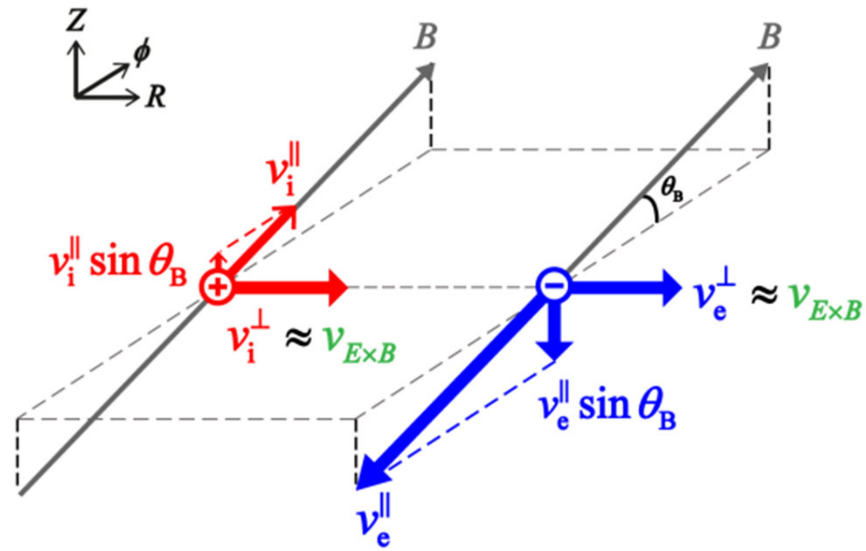
- ➔ ExB vortices at plasma edges are turbulent due to negligible viscosity
- ➔ Plasma rapidly diffuses along B_{RZ} by turbulent mixing
- ➔ Homogeneous plasma density along B_{RZ}

➔ **Dominant transport mechanism in the RZ plane when $n > n_{\text{crit},\perp} \equiv \left(\frac{\epsilon_0 B^2}{m_e}\right) \tan^2(\theta_B) \left(\frac{1}{\gamma}\right)^2$**

Toroidally symmetric plasma model

Dominant ExB transport in the RZ plane





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

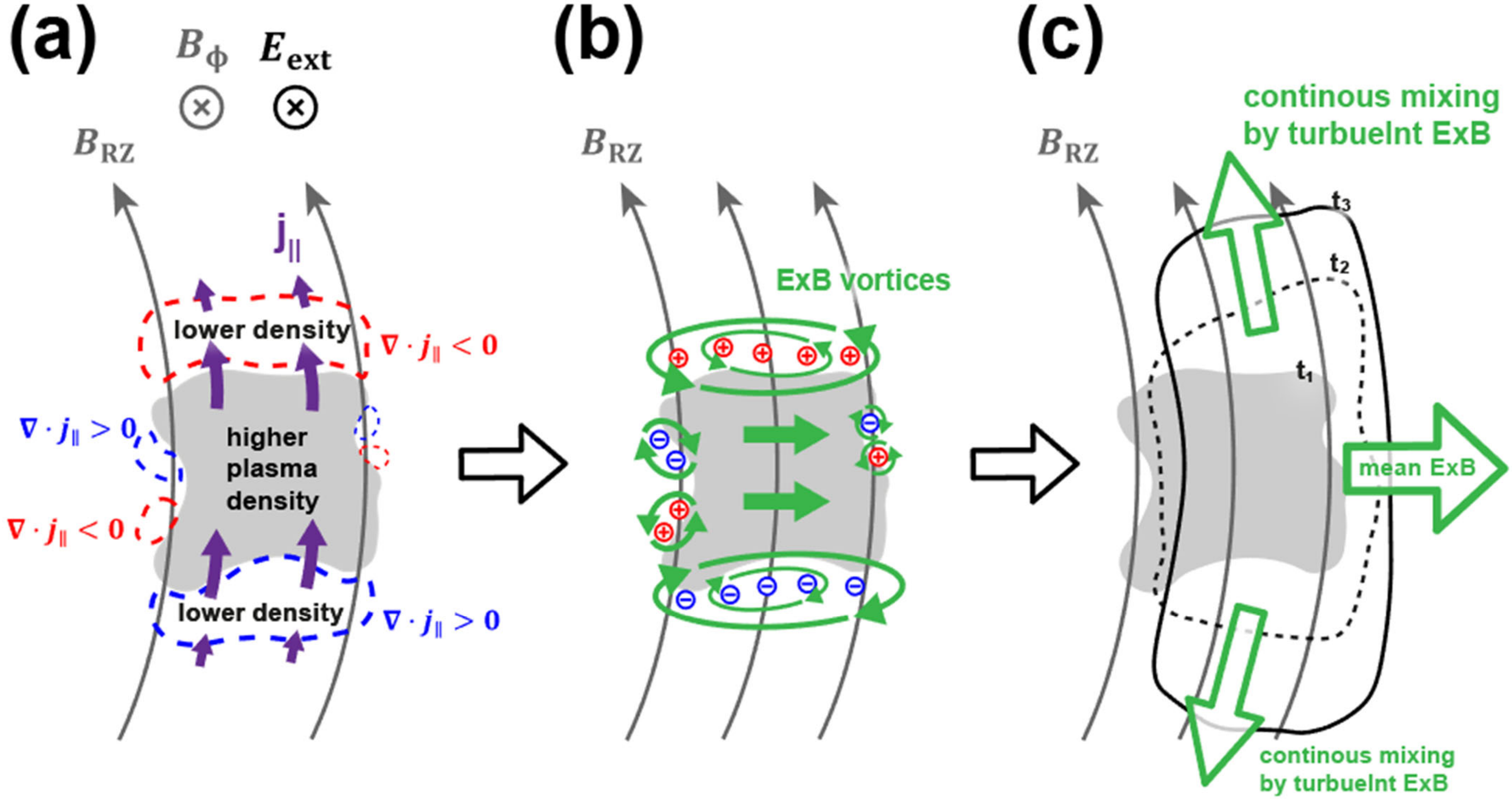
$$v_e^{\perp} \approx v_i^{\perp} \approx v_{E\times B} \gtrsim v_e^{\parallel}\sin\theta_B \gg v_i^{\parallel}\sin\theta_B$$

$1000\ m/s$ $1000\ m/s$ $1\ m/s$

Perpendicular critical density

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

Toroidally symmetric plasma model
Perpendicular dynamics



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

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

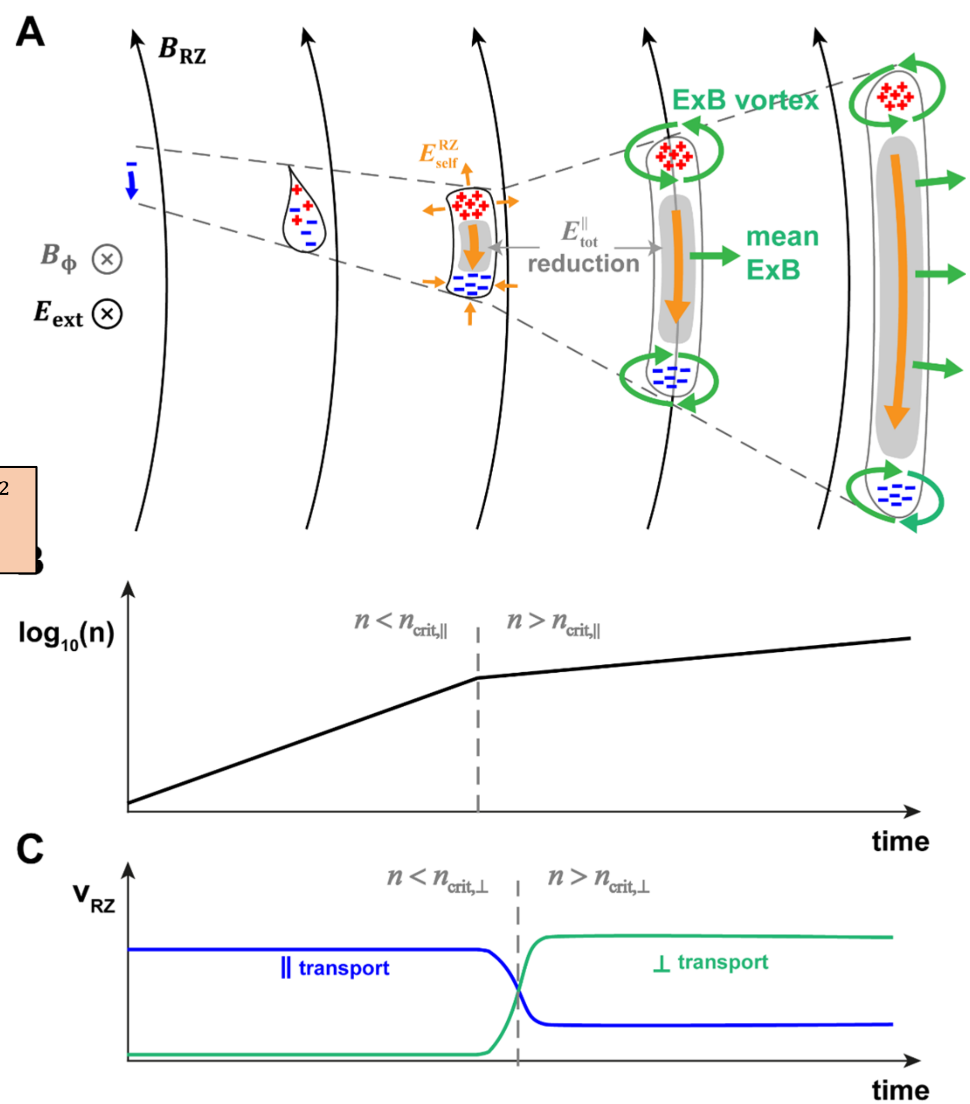
2. **Mean ExB across B_{RZ}**

   ➔ **Determine plasma position**

   ➔ **Dominant plasma loss term**

3. **Turbulent ExB mixing along B_{RZ}**

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



Particle simulation (BREAK)

Development of particle simulation code

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

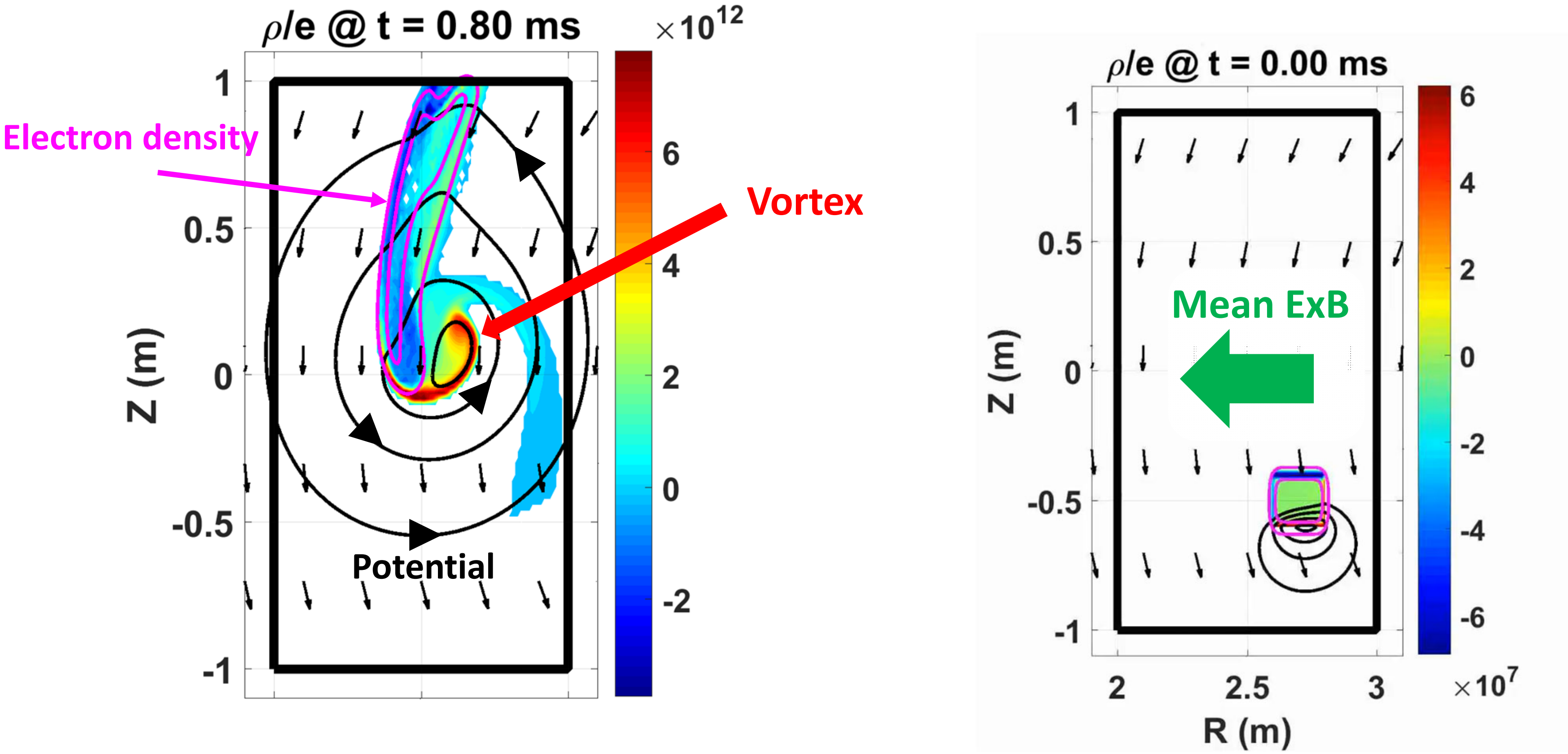
- **The ohmic breakdown phenomena span a broad range of spatio-temporal scales**

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

- **BREAK** (**B**reakdown **R**ealistic **E**volution **A**nalysis in tokama**K**) **(YOO, CPC 2017)**

  - **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)**

Particle simulation (BREAK)
ExB mixing avalanche simulation in simple EM fields



✓ **BREAK simulation demonstrated the significant roles of self-electric fields**

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**

$$n_{\text{gas}} = 4 \times 10^{17}\ m^{-3}$$

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

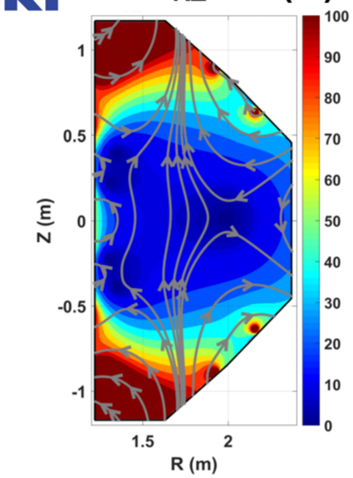
- **2 different simulations**

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

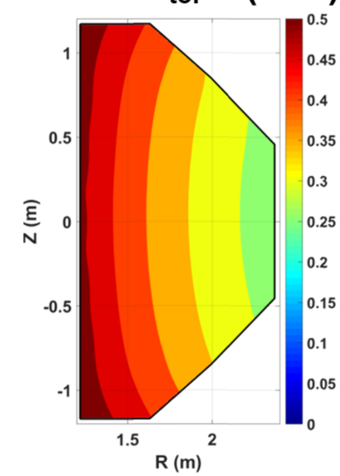
difference

t = 30 ms

$|B_{RZ}|$ (G)



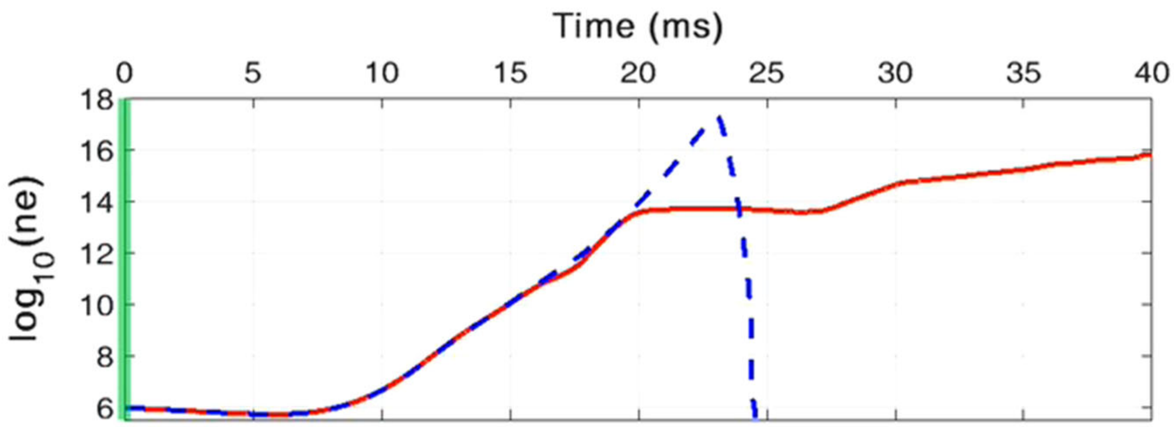
$|E_{tor}|$ (V/m)



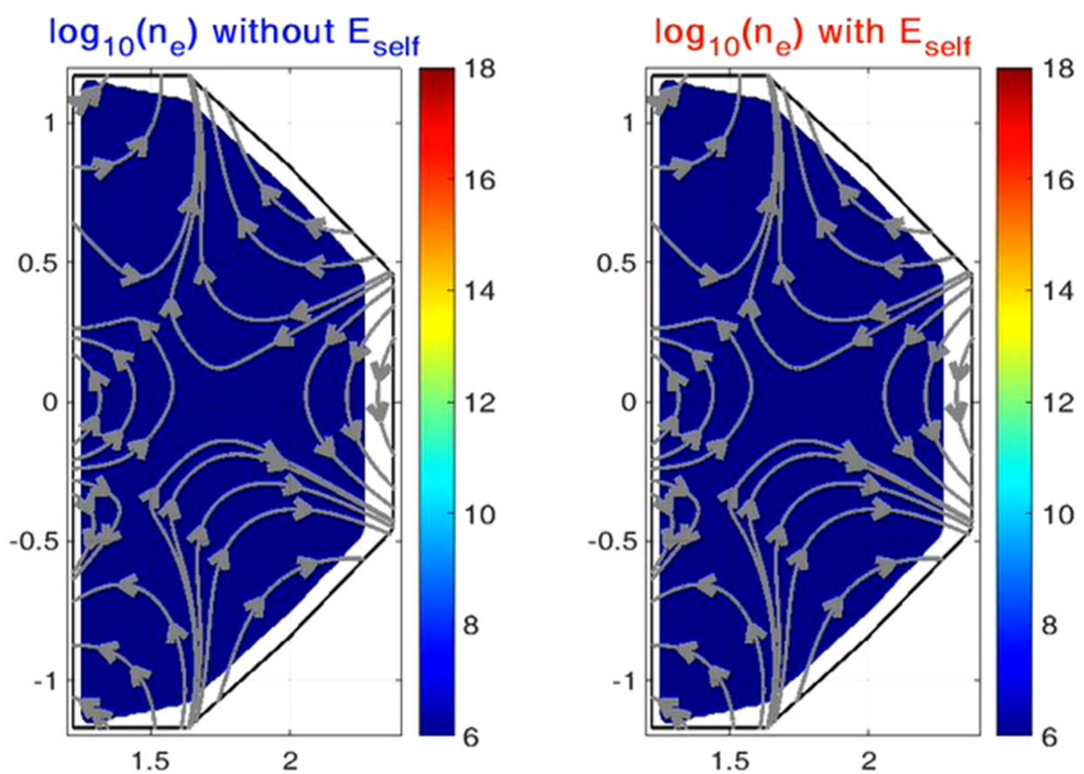
[6] Jayhyun Kim, *et al.*, Nucl. Fusion 51 083034 (2011)

Particle simulation (BREAK)

Main results of KSTAR simulation



t = 0.0 ms



✓ **without E_{self}**

- **Monotonic exponential growth**
- **Parallel transport**

✓ **with E_{self}**

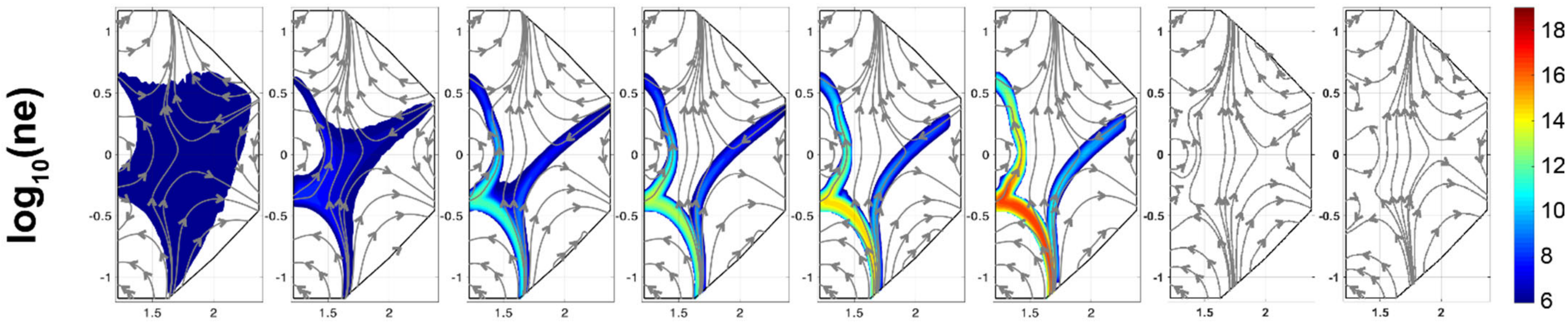
- **Reduction of growth rate**
- **Anomalous perpendicular transport**

Particle simulation (BREAK)

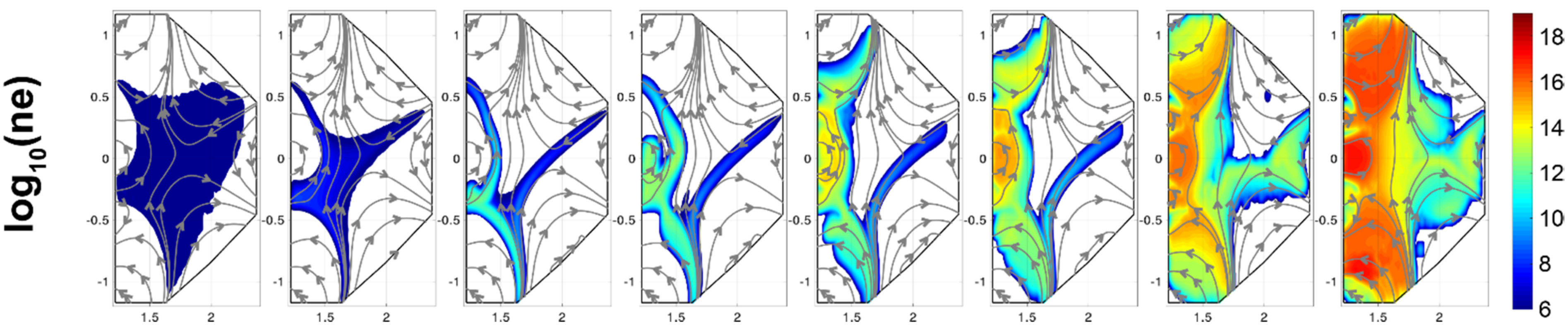
Main results of KSTAR simulation

✓ without E_{self}

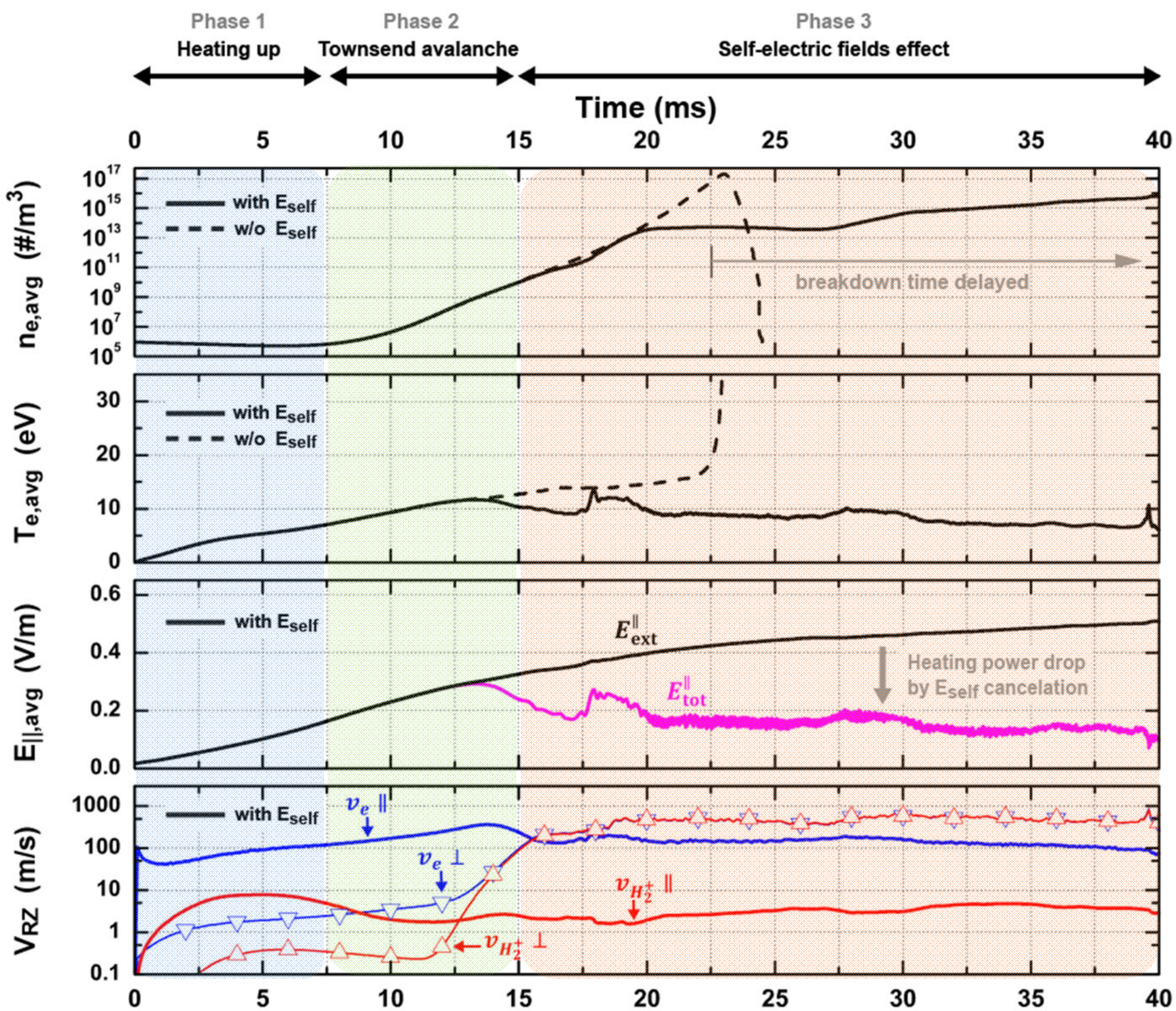
5 ms | 10 ms | 15 ms | 17 ms | 19 ms | 21 ms | 30 ms | 40 ms



✓ with E_{self}



Particle simulation (BREAK)
0D results of KSTAR simulation

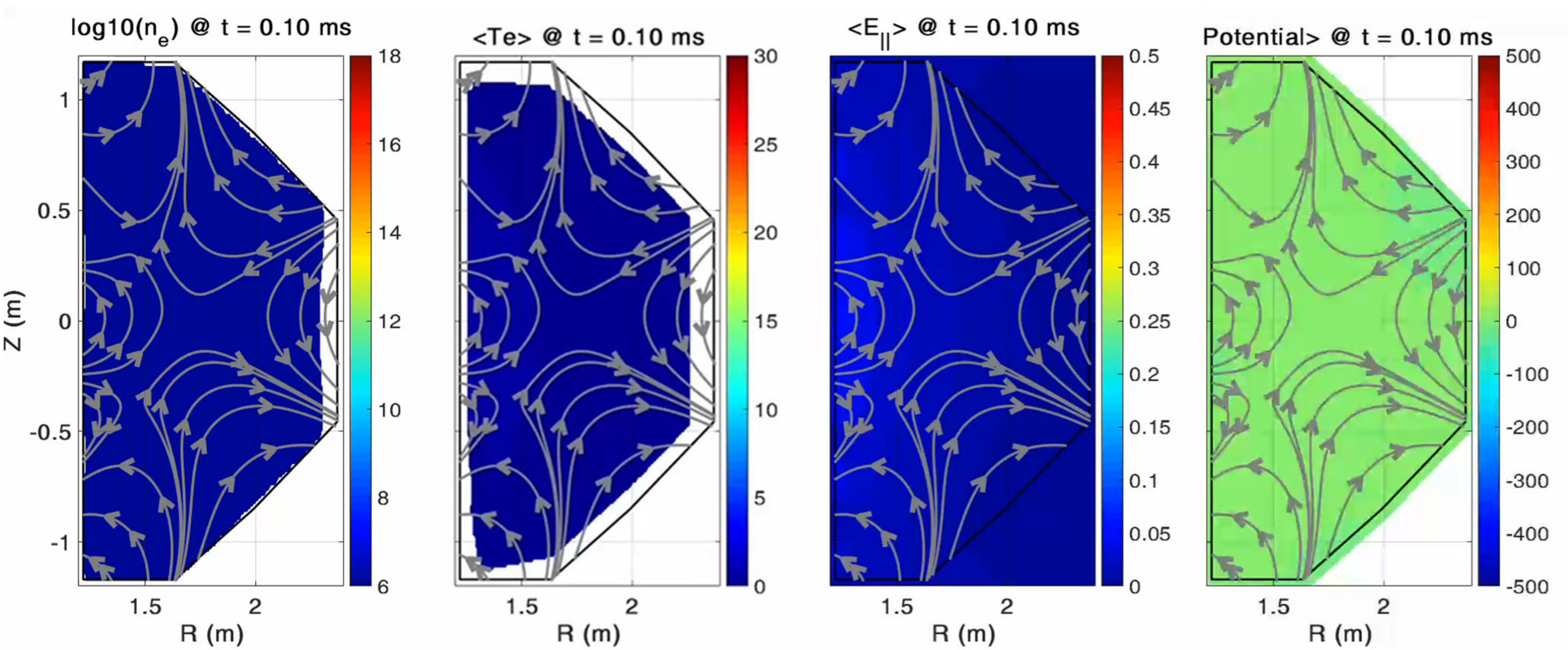


- **Plasma T_e & n_e**
  - Maintaining low Te (~ 10 eV)
  - Drastic decrease of n_e growth rate
- **Parallel heating**
  - $E^{\|}_{self}$ cancels out $E^{\|}_{ext}$ ($E^{\|}_{tot}$ ⬇)
  - Heating power is reduced
- **Transports**
  - $v_e \parallel$ is reduced
  - Perpendicular transports by ExB
  -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

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

Particle simulation (BREAK)
Phase 1-2 : Heat up and Townsend avalanche (0 – 15 ms)

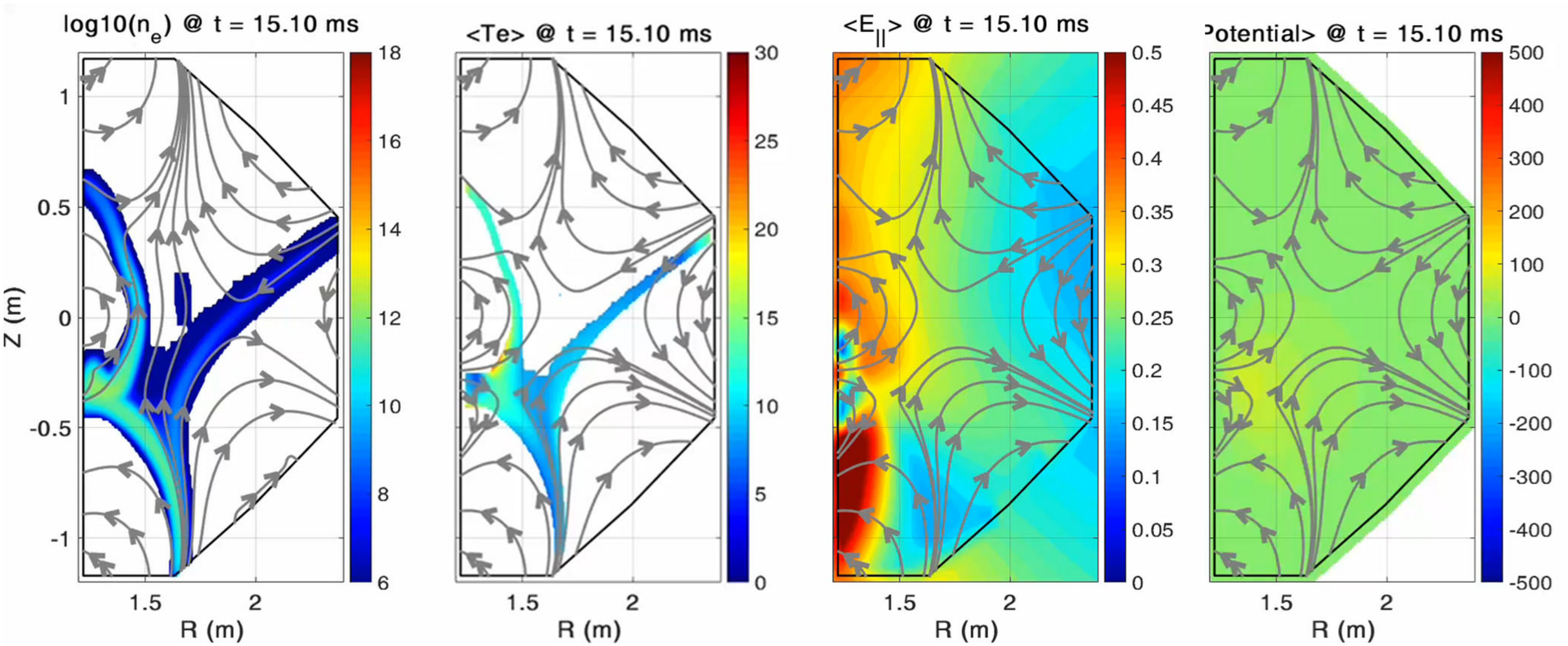
$\log_{10}(n_e)$ $\mathrm{T_e}$ (eV) $|E_\parallel|$ (V/m)   **Potential (V)**



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

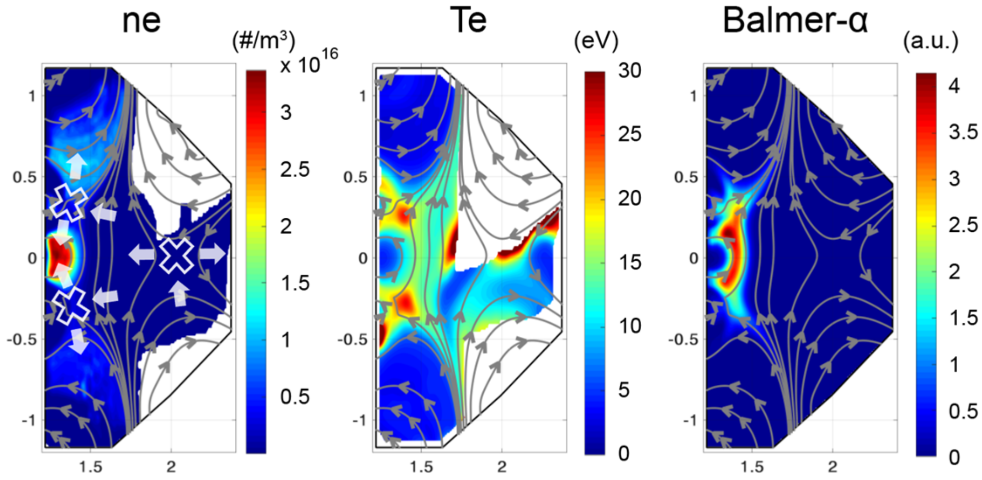
Particle simulation (BREAK)
Phase 3 : Self-electric fields dominated (15 – 40 ms)

$\log_{10}(n_e)$ T_e (eV) $|E_{\parallel}|$ (V/m)   Potential (V)

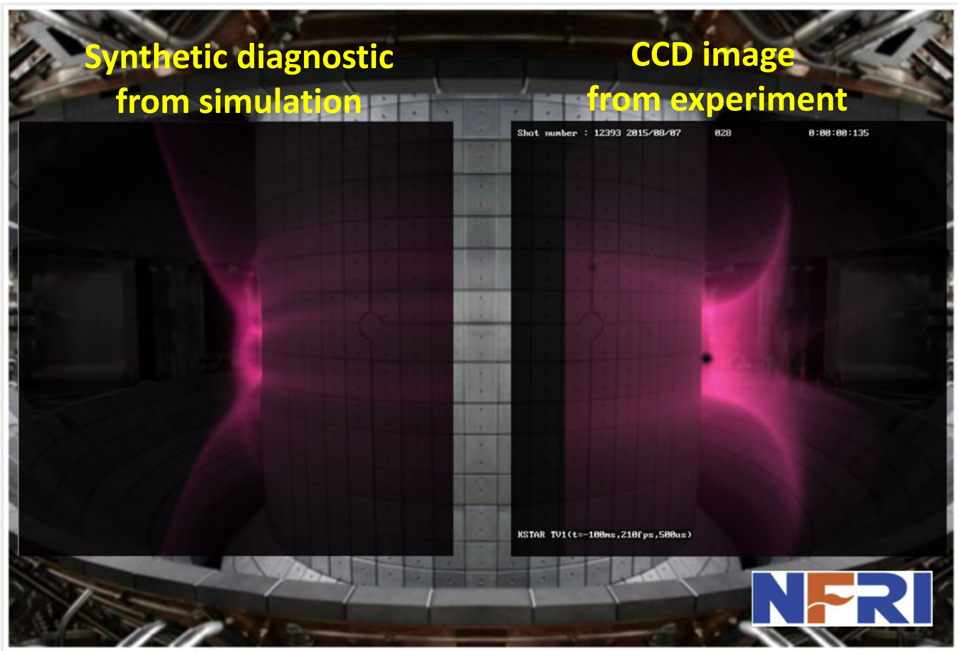


- ✓ **Slower growth rate**
- ✓ **Elongated plasma structure due to ExB perpendicular transports**
- ✓ **Strongly inhomogeneous plasma density and temperature**

Particle simulation (BREAK)
Comparison with experiments



- **Densities are higher at downstream regions**
- **Temperatures are lower at downstream regions**
- **Discrepancy between Balmer-α line emissions and electron density is observed**



- **CCD camera image shows emission structure at the inboard side along $\mathbf{B}_{RZ}$**
- **Synthetic diagnostic well agrees with experiments qualitatively**
- **The differences result from uncertainties of initial conditions, magnetic field structure and camera view information**

Implications for scenario design strategy

Mean ExB (Perpendicular dynamics)

- **Mean ExB flow can have arbitrary direction depending on electromagnetic topology**

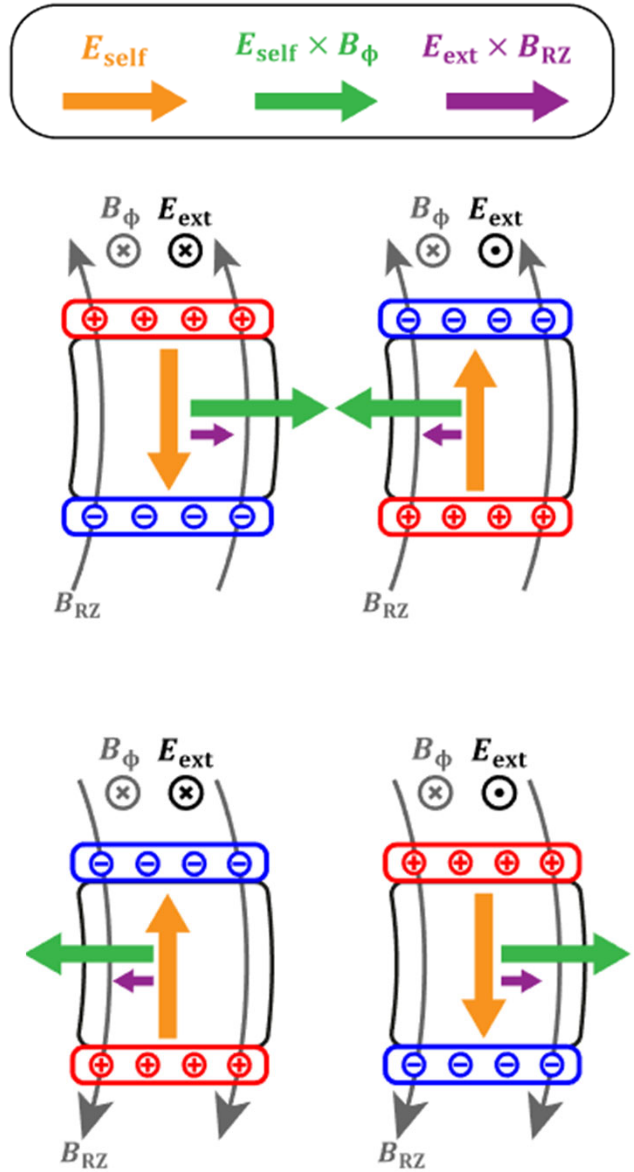
- **Easily predictable from external EM fields only**

$$v_{E_{self}\times B_\phi} \quad // \quad v_{E_{ext}\times B_{RZ}}$$

1000 m/s ↓

$$\frac{\left|v_{E_{self}\times B_\phi}\right|}{\left|v_{E_{ext}\times B_\phi}\right|} = \cot^2(\theta_B) = 10^5 \sim 10^7$$

↑ **0.001 m/s**



Implications for scenario design strategy
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

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

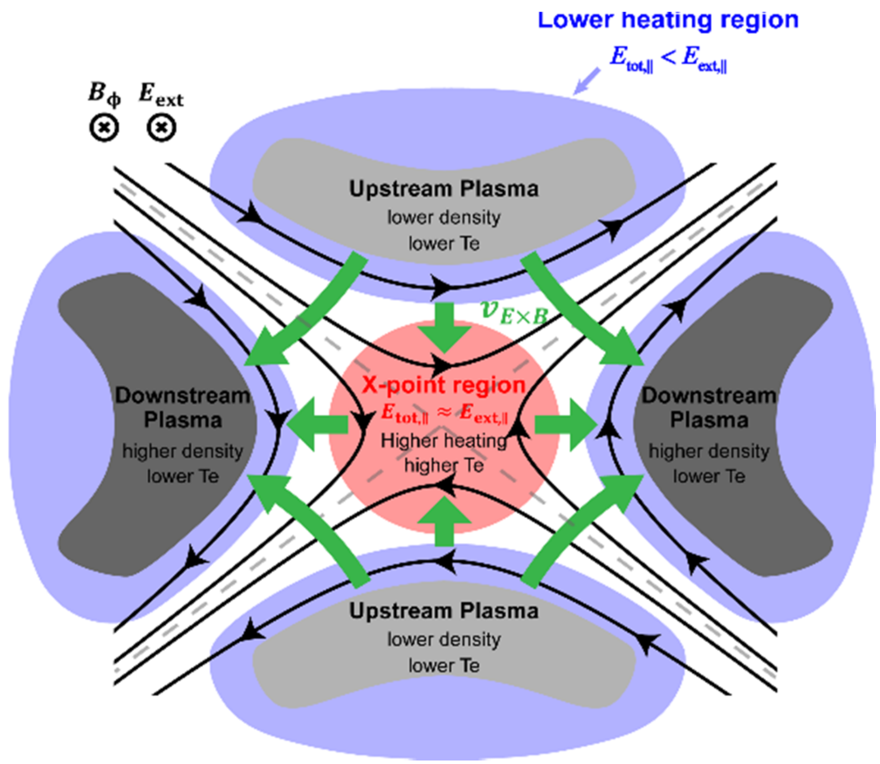
- Lower heating at other regions

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

Perpendicular dynamics

- Two inflows + Two outflows by mean ExB

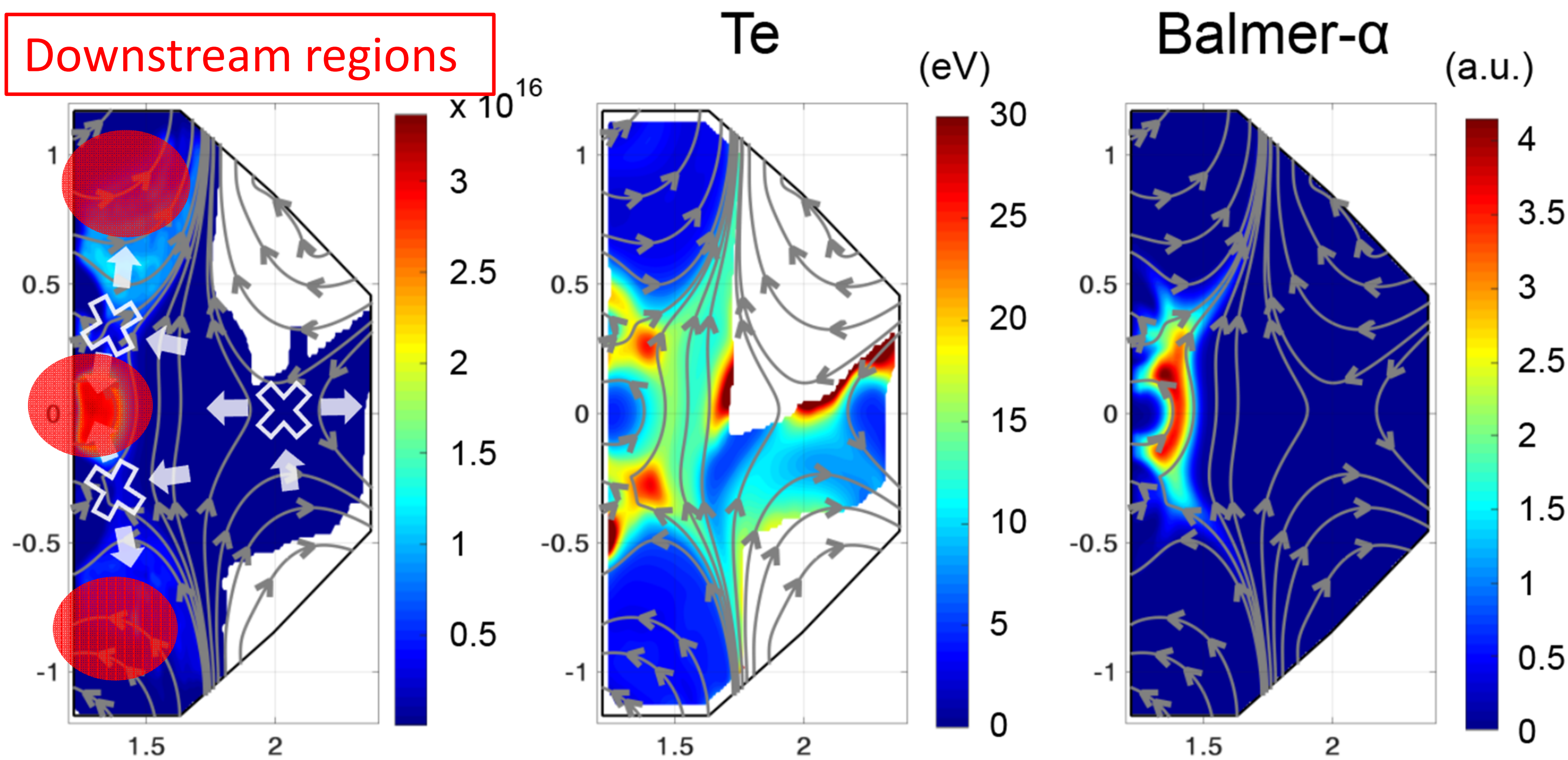
  $n > n_{\mathrm{crit},\perp}$



➡ **Topology analysis** on external EM fields predicts overall plasma evolution

➡ **Plasma density would be higher at downstream region**

Implications for scenario design strategy
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**

Implications for scenario design strategy
New guidelines for scenario design

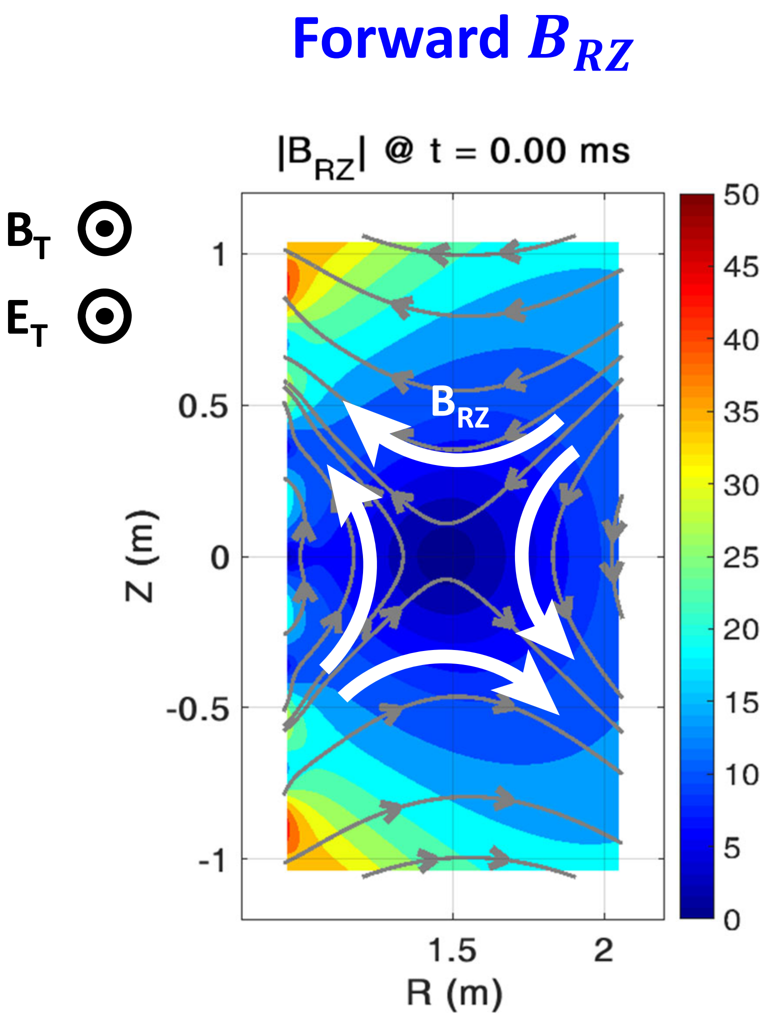
Topology analysis method can predict overall spatial-temporal plasma evolution

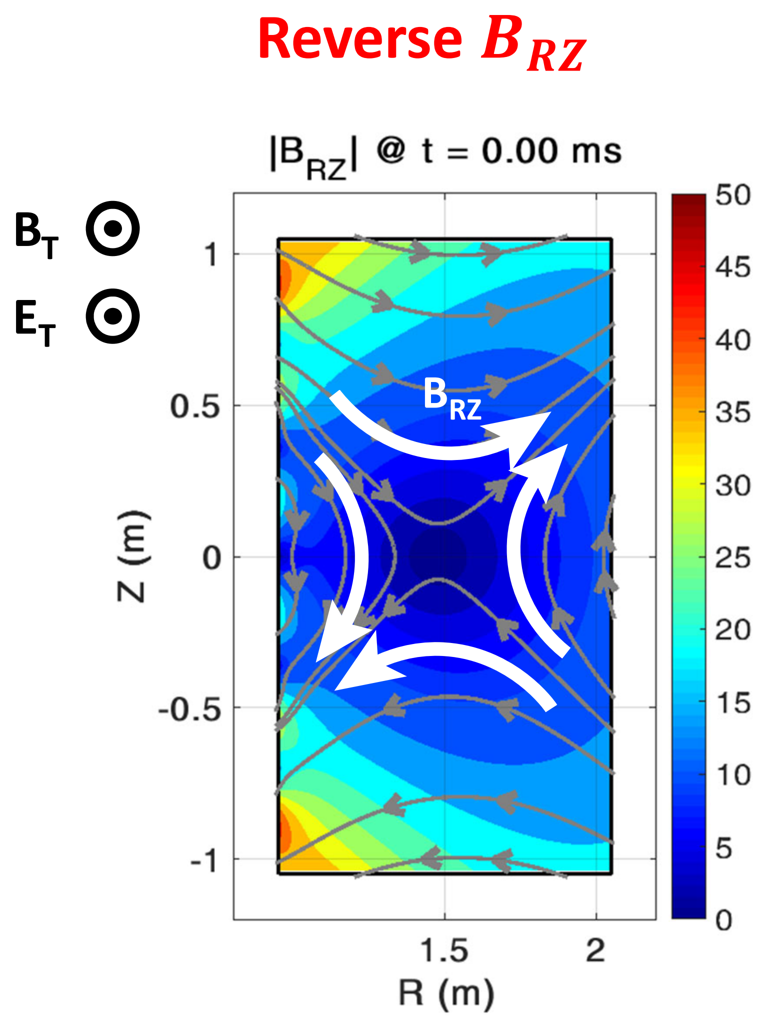
- Main plasma position (High-density at downstream region)
- Inhomogeneous structure of plasma density and temperature
- New confinement time restricted by mean ExB convective loss ($\tau_{\perp} \sim a/v_{E\times B}$)

Breakdown scenario can be optimized by controlling X-point topology for

- Robust ohmic breakdown for low-E field operation
- Position control of initial closed surface
- Vertical stability control using PCS
- Effective ECH deposition (ex. Targeted to downstream region, not for X-point)

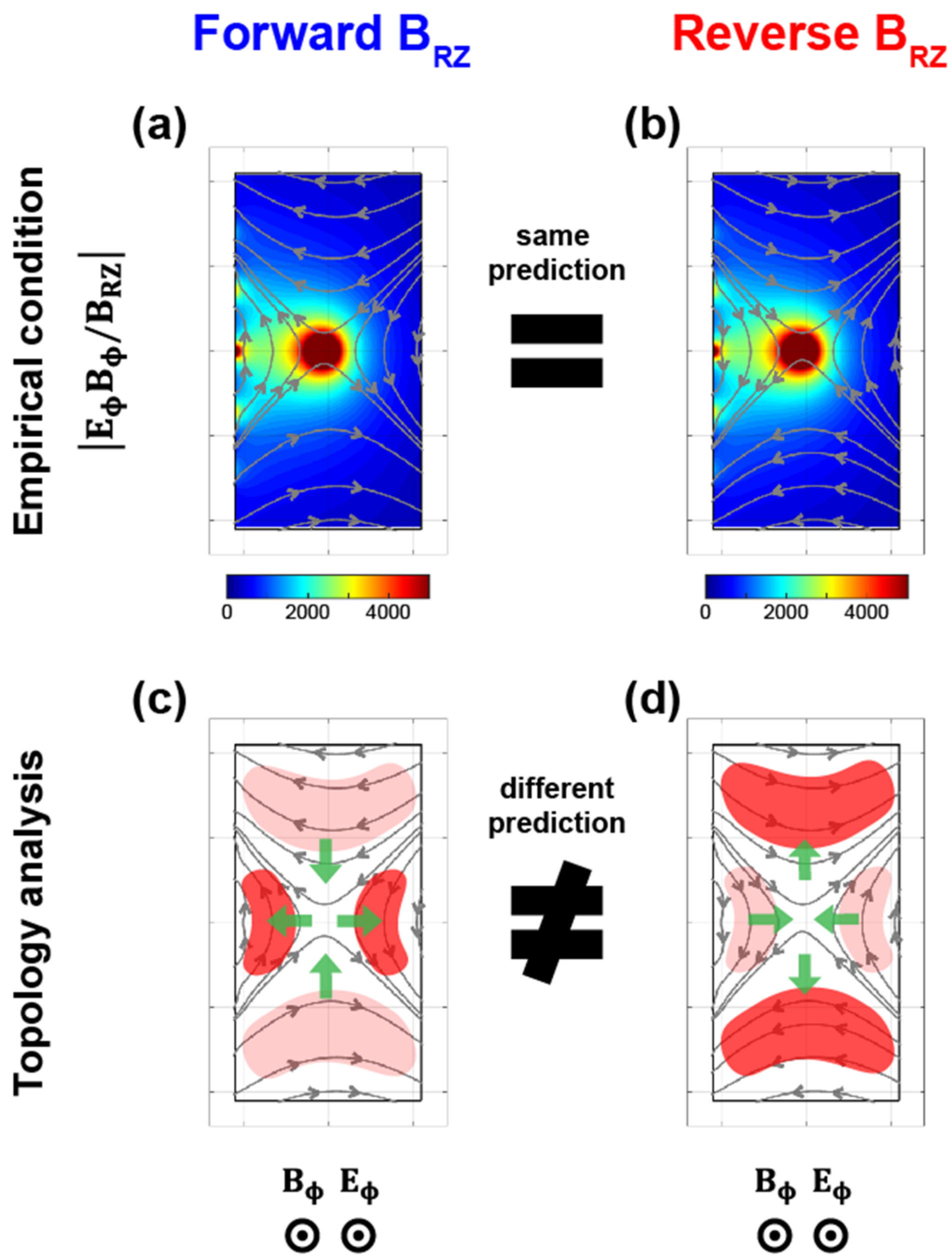
New guidelines for scenario design





➡ **Same magnitudes, but opposite direction of B_{RZ}**

Implications for scenario design strategy
New guidelines for scenario design



✓ (Previous) **Empirical condition**

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

✓ (New) **Topology analysis method**

Predicted mean ExB

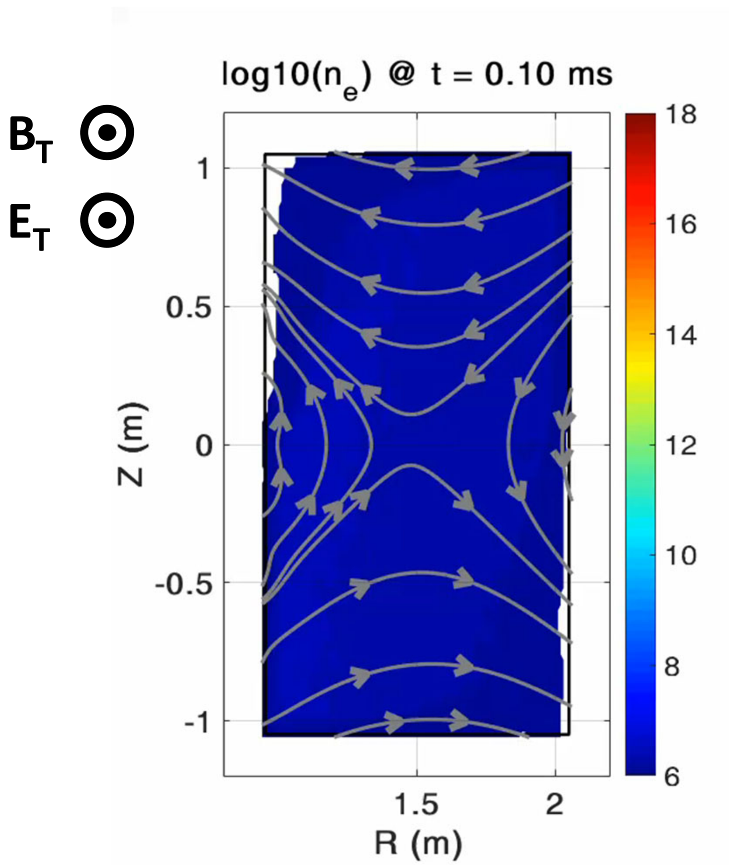
Upstream region
Low plasma density

Downstream region
High plasma density

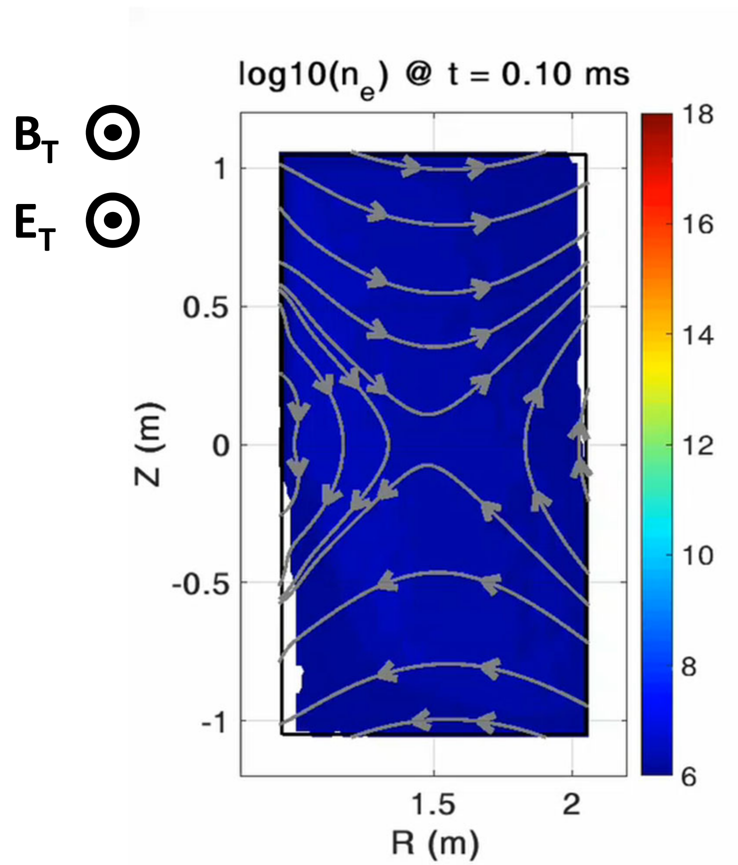
- Different prediction for 2 cases
- High plasma density at downstream region

New guidelines for scenario design

Forward B_{RZ}



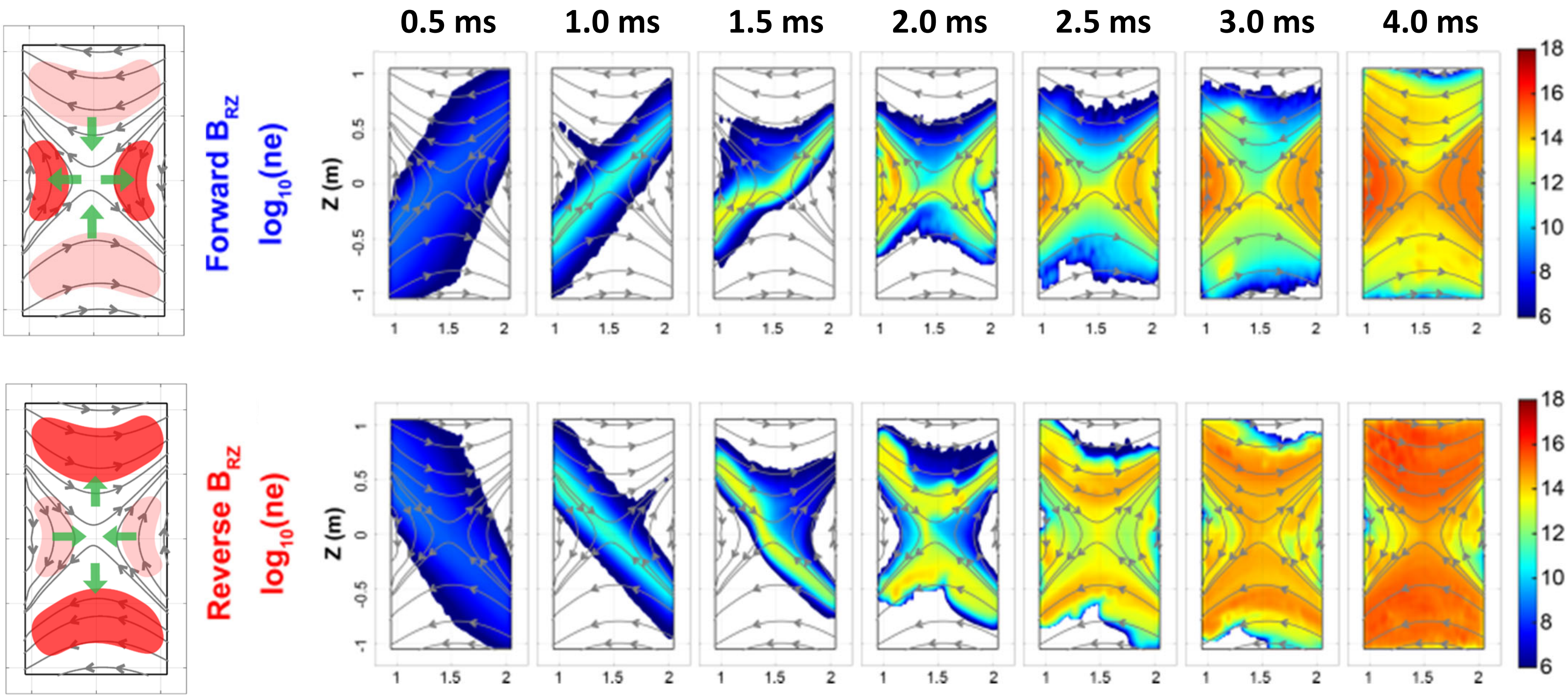
Reverse B_{RZ}



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

Implications for scenario design strategy
New guidelines for scenario design

Topology analysis

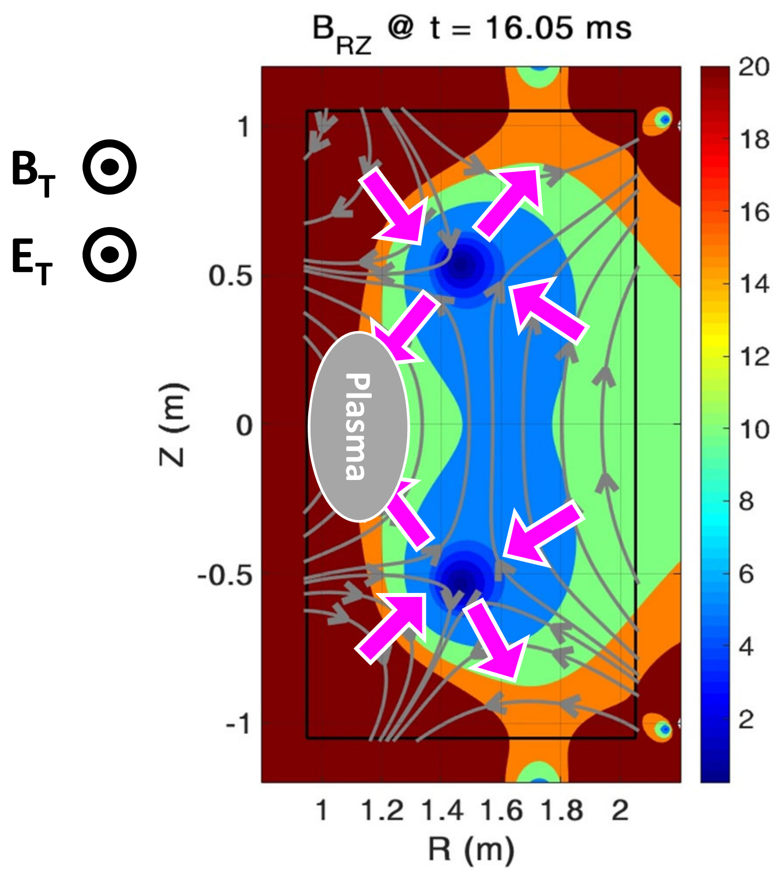


➡ Topology analysis method **well predicted the plasma behaviors**

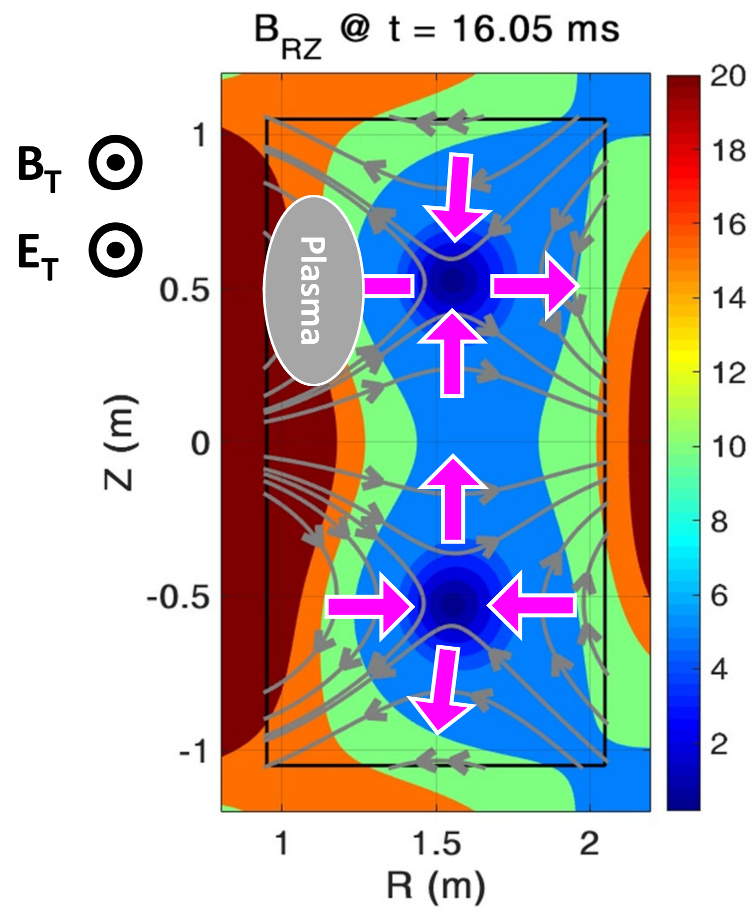
Implications for scenario design strategy

New guidelines for scenario design

Artificial Double Null case 1

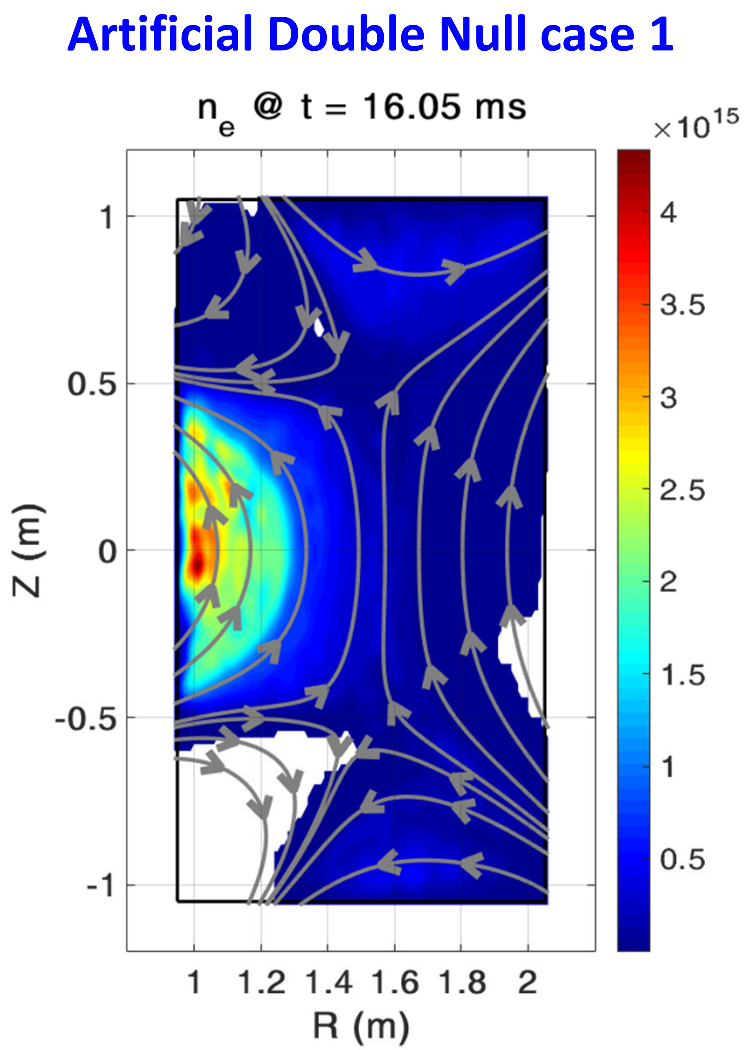


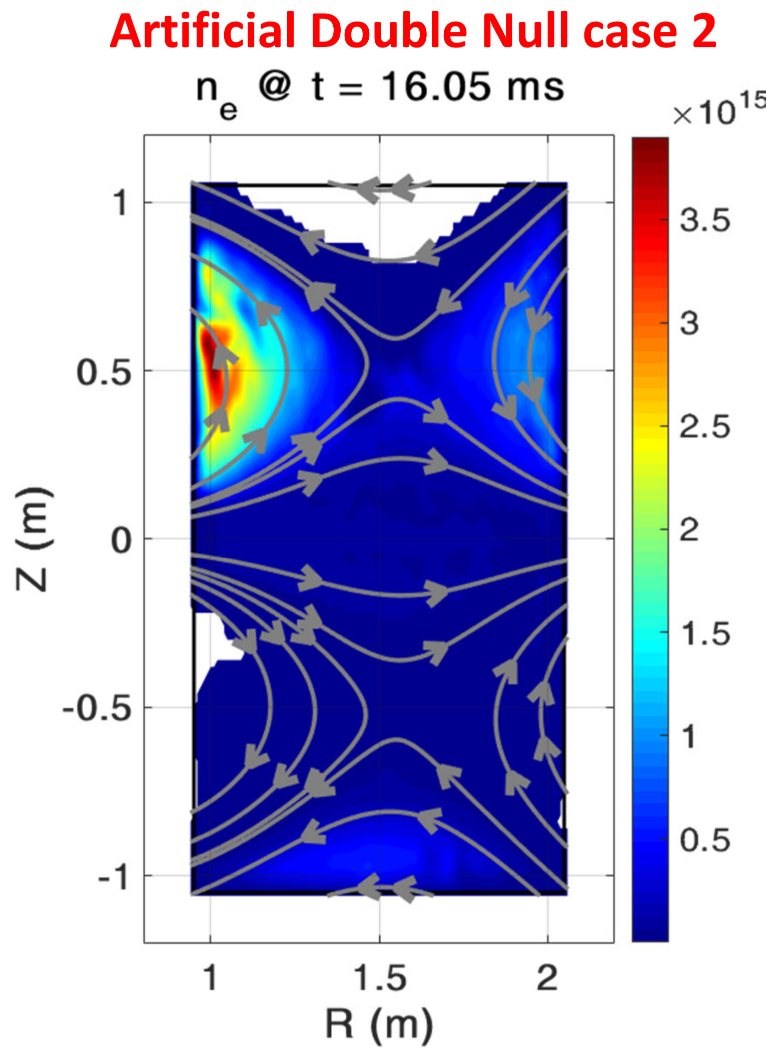
Artificial Double Null case 2



Plasma behaviors and positions could be predicted by topology analysis

Implications for scenario design strategy
New guidelines for scenario design





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

Conclusion

- **Ohmic breakdown physics has not been revealed due to its complexity**

- **We propose novel mechanisms of ohmic breakdown by considering plasma response self-consistently which can explain mysterious experimental results**

- **Crucial roles of self-electric fields** as underlying mechanism are **newly discovered**

  ✓ **Cancellation of external electric fields** **(parallel)**

  - Parallel transport ⬇ Heating power ⬇ Electron temperature ⬇ Avalanche growth rate ⬇

  - 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 into the complex EM topology can provide general guidelines for robust breakdown scenario strategy**