The 15th International Symposium for Space Simulations (ISSS-15)
and
the 16th International Workshop on the Interrelationship between Plasma Experiments in the Laboratory and in Space (IPELS-16)

Effects of spontaneously-generated and artificially-controlled electrostatic fields in high guide-field magnetic reconnection in laboratory experiment

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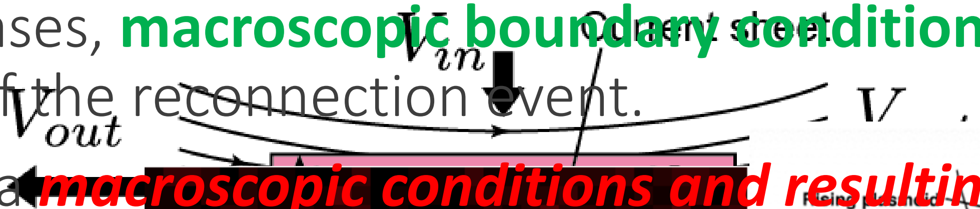
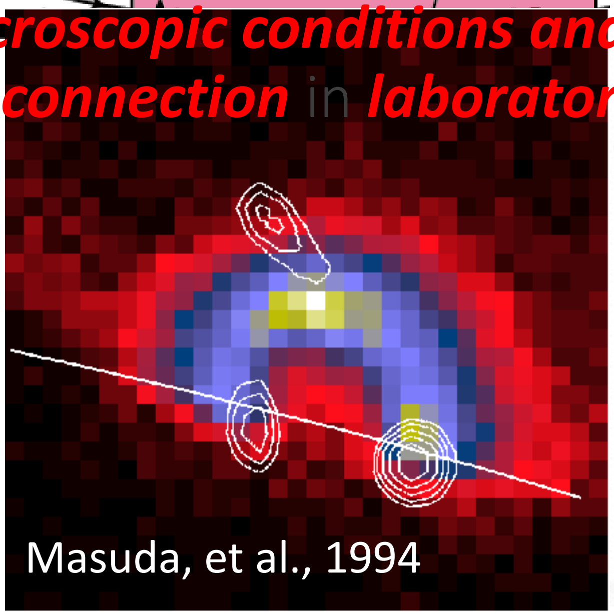
and the UTST team
(Univ. Tokyo)

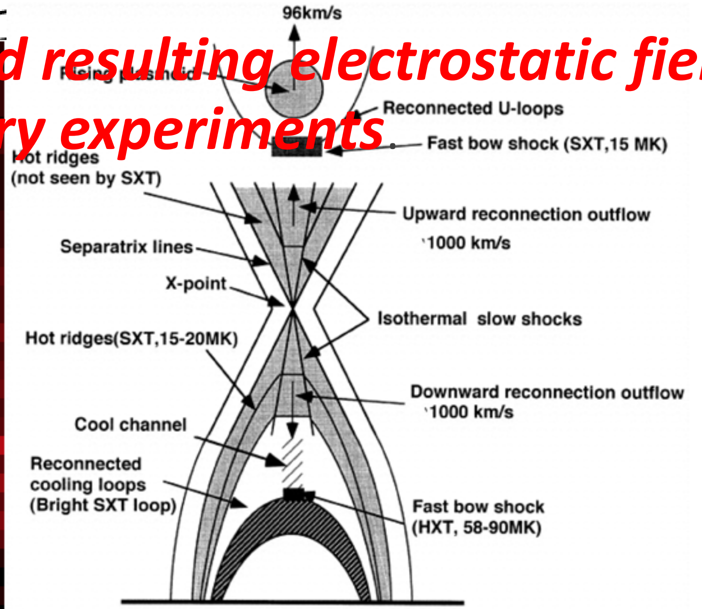
Key points of this talk

- ✓ Magnetic reconnection is ubiquitously observed in magnetized plasmas in astro, space, solar and laboratory experiments.
- ✓ Many features of reconnection is **originated from microscopic reconnection region** (and maybe from the separatrices).
- ✓ However, in some cases, **macroscopic boundary conditions significantly affect** the overall picture of the reconnection event.
- ✓ This talk focuses on a ***macroscopic conditions and resulting electrostatic field*** on the ***guide-field (GF) reconnection*** in ***laboratory experiments***.



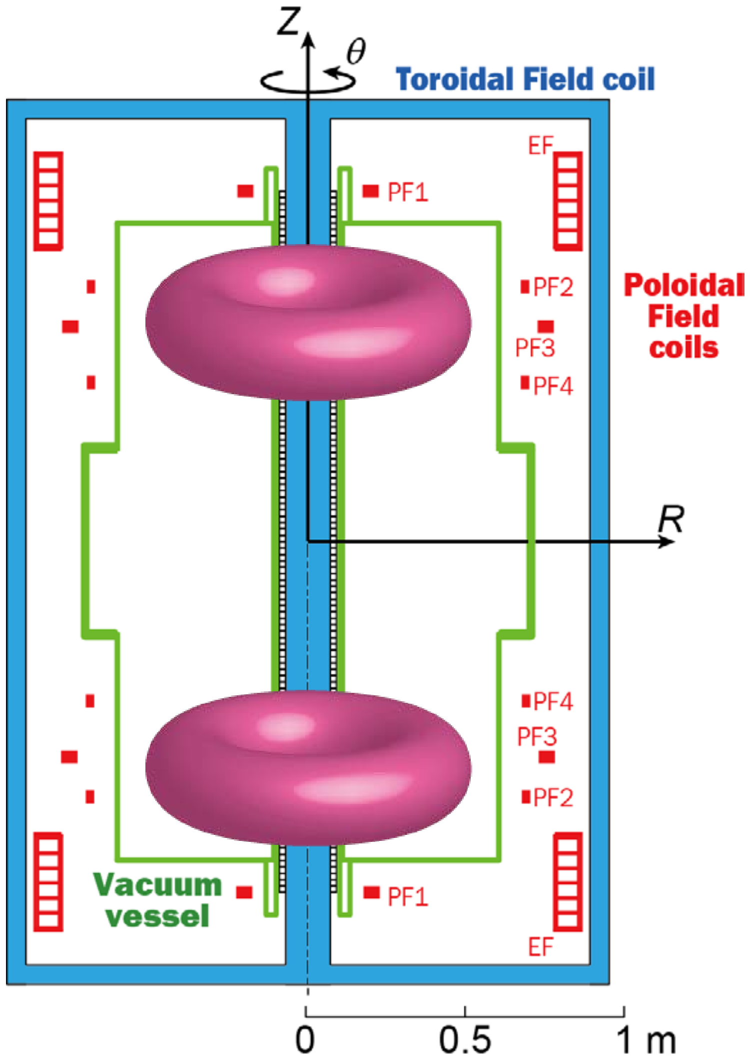


Masuda, et al., 1994



Tsuneta 1997

What kind of experiment?



0. Experimental setup is axisymmetric. Steady toroidal magnetic field (high-GF) is applied by the coil current.

1. Two torus plasmas (flux tubes) are formed.

2. Two torus plasmas move toward center of the device and merge through magnetic reconnection.

Outline

Introduction

Experiment-specific conditions

- Geometry
- Source of magnetic field : plasma current and coil current
- Boundary conditions : particle, magnetic, electric

Macroscopic electrostatic fields

Effects of macroscopic electrostatic fields

- ExB outflow velocity
- Particle acceleration
- Plasma current profile

Conclusion

Introduction

✓ Magnetic reconnection process is actively used in fusion research field as a **merging start-up scheme of spherical tokamak** (ST) plasmas. High power ion heating with favorable scaling $\Delta T_i \sim B_{rec}^2 \sim I_p^2$ leads to dynamic formation of ST with keV-order T_i.

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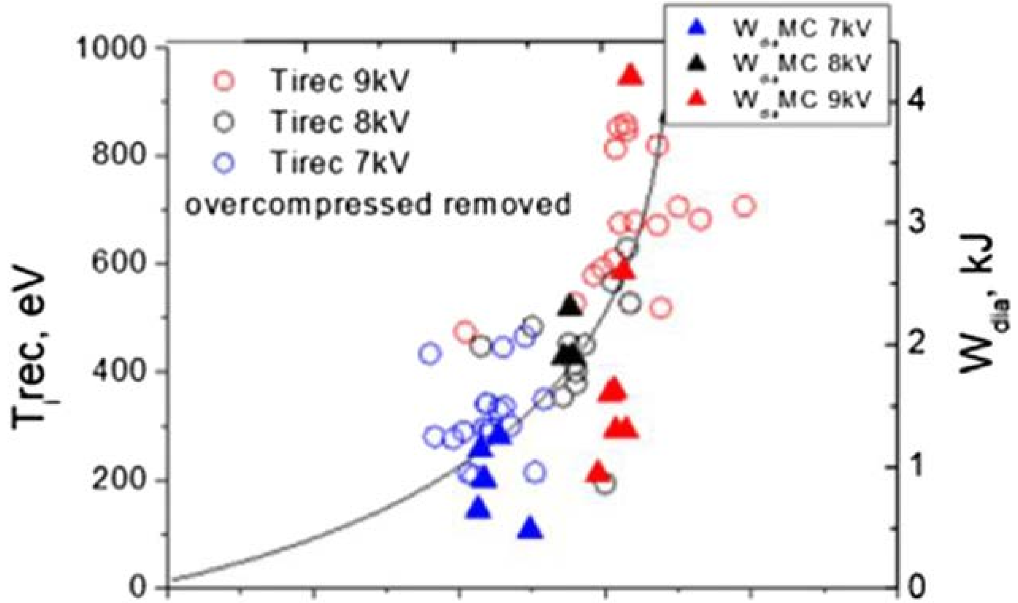
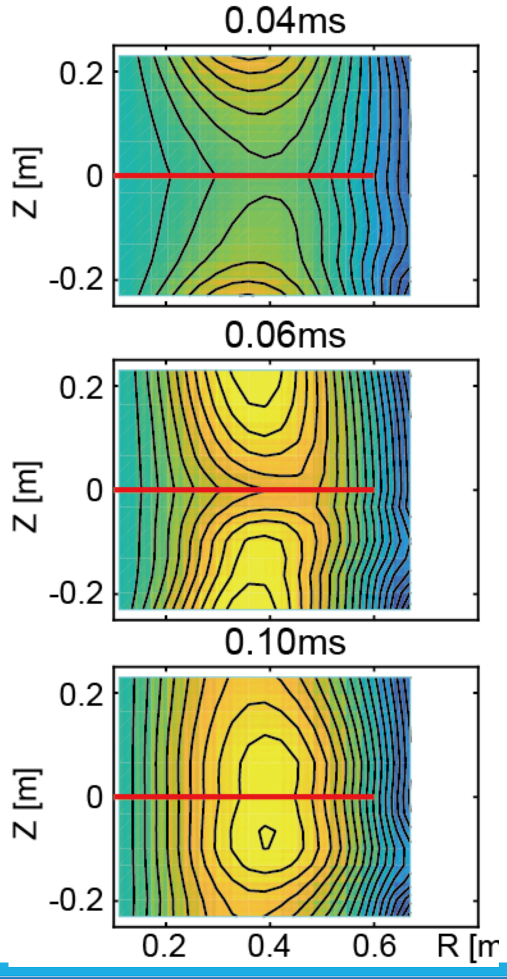
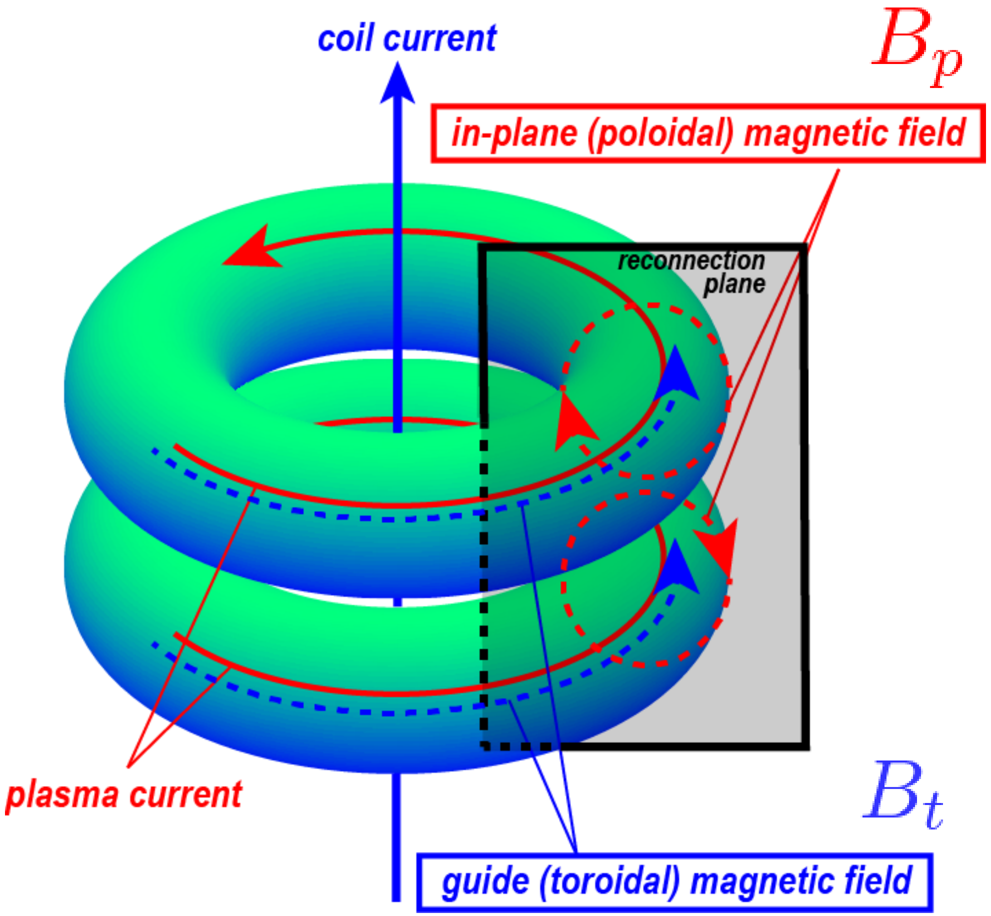


Highly effective ion energization in magnetic reconnection is attractive in fusion plasma research, and further improvements are required in analysis of phenomena and experimental techniques.

Experiment-specific conditions

- ✓ Magnetic fields involved in an axisymmetric torus experiment has two origins: plasma current and coil current.

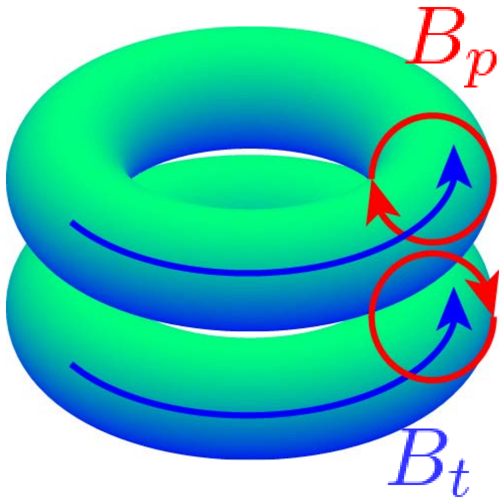




Experiment-specific conditions

CONDITION A High GF ratio

$$B_{guide} \gg B_{reconnection}$$



CONDITION B

Axisymmetry

$$\frac{\partial}{\partial \theta} \sim 0$$

B_t by coil current $\gg$ B_p by plasma current

$$\frac{\partial B_t}{\partial t} \sim 0 \qquad \frac{\partial B_p}{\partial t} \neq 0$$

poloidal flux

$$\oint_{c_t} E_{t,ind}\, dl = -\frac{d\Psi}{dt}, \quad E_{t,sta} \sim 0$$

Out-of-plane *E* is **inductive**.

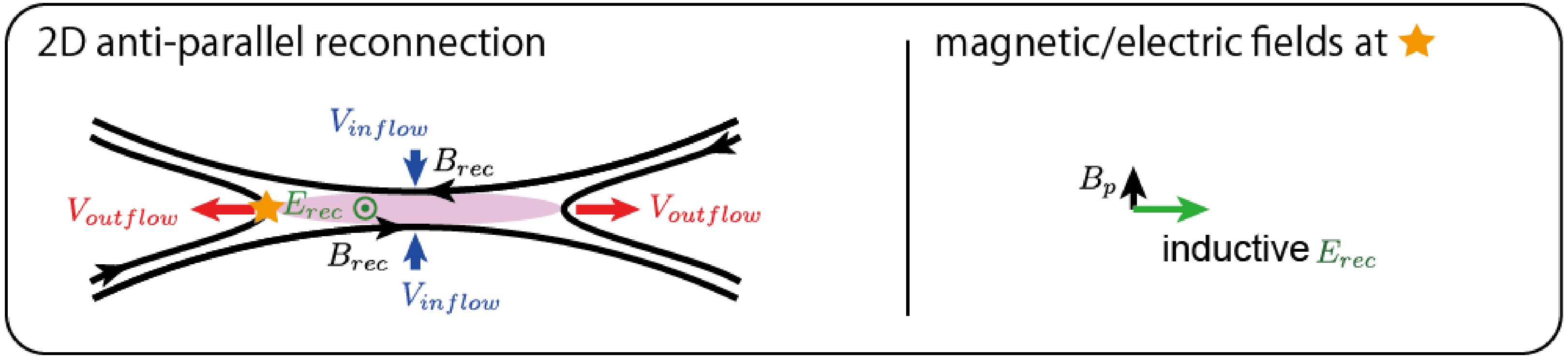
toroidal flux

$$\oint_{c_p} \boldsymbol{E}_{p,ind} \cdot d\boldsymbol{l} = -\frac{d\Phi}{dt} \sim 0$$

In-plane inductive *E* is negligible.

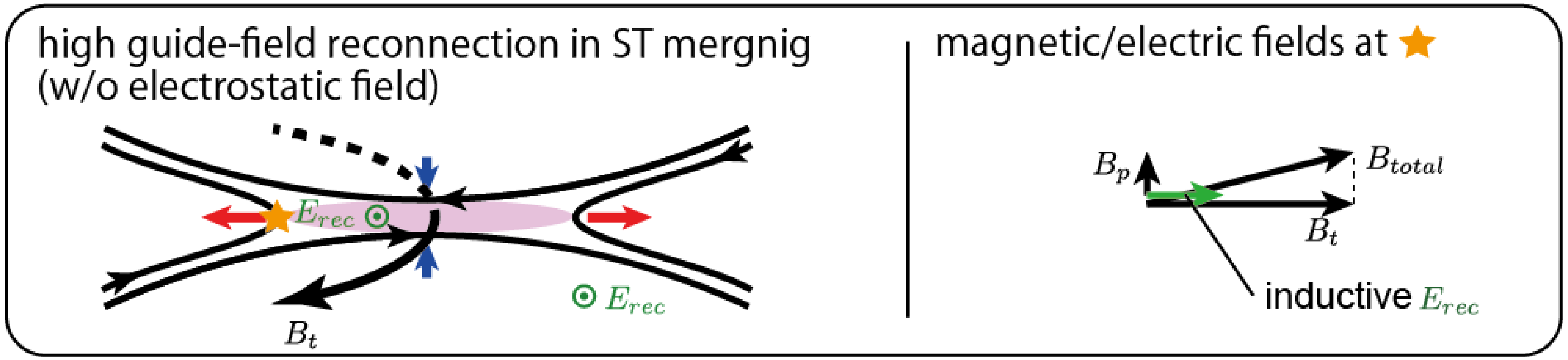
CONDITION C $\boldsymbol{E}_p$ necessary to satisfy the Ideal MHD condition $\boldsymbol{E} + \boldsymbol{u} \times \boldsymbol{B} = 0$ (or $\boldsymbol{E} \perp \boldsymbol{B}$) in the upstream/downstream regions is **mostly electrostatic field**.

Anti-parallel reconnection



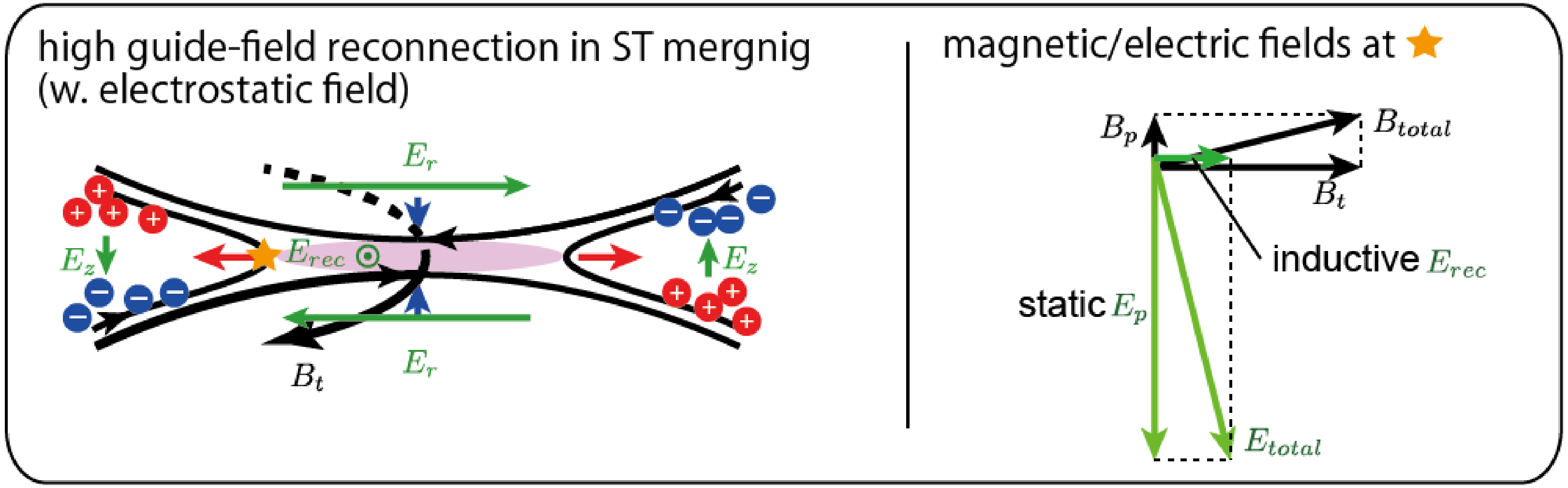
High GF reconnection

(inductive electric field only)



High GF reconnection

(Electrostatic field for satisfying ideal MHD condition in downstream)



High GF reconnection in ST merging

In-plane electrostatic field E_{sta} is essential to hold the ideal MHD condition in the upstream and downstream regions.

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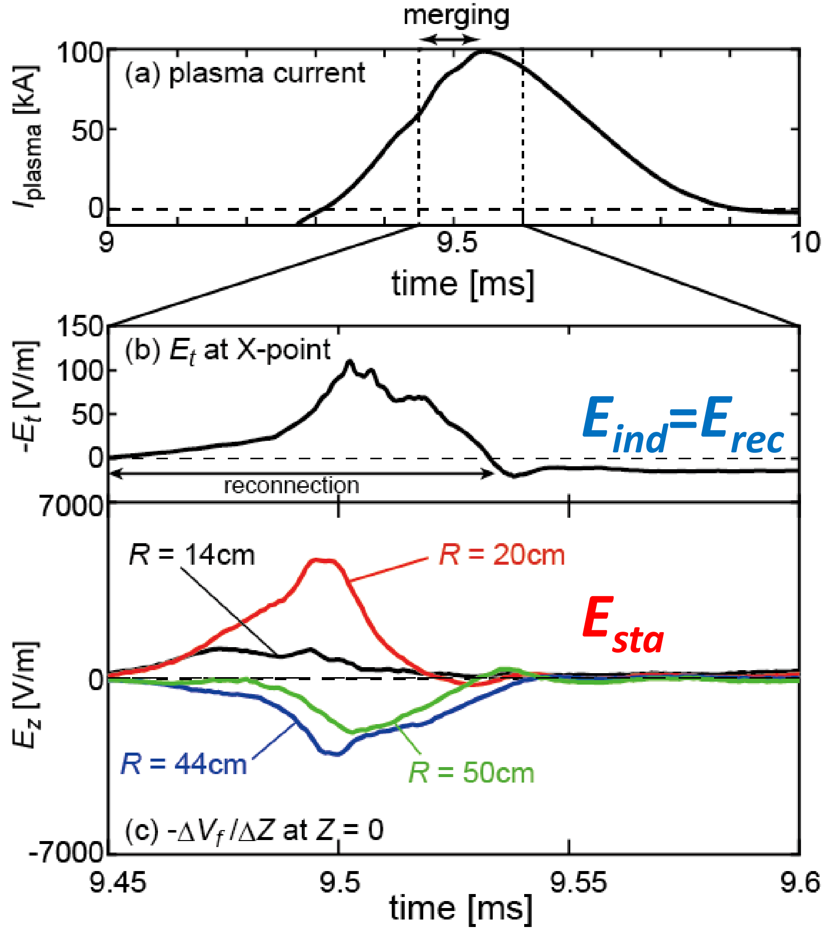
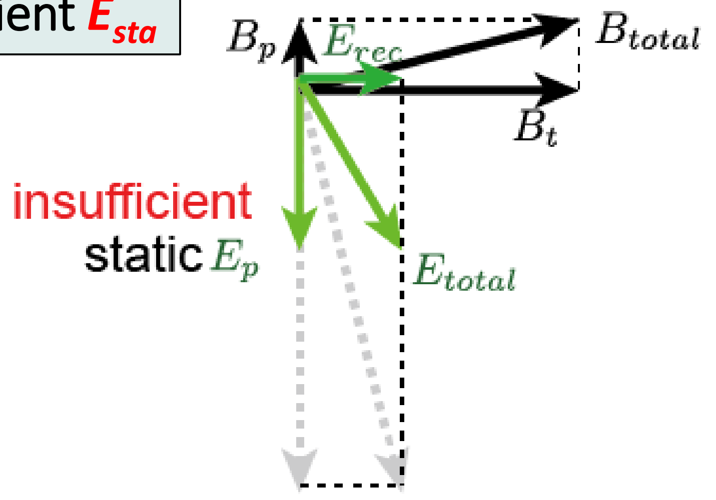
- ✓ At first, we expected that E_{sta} grows to a level that roughly cancel $E_{//}$ because $\tau_{\rm rec} > \tau_{\rm e,transit} \gg 1/\omega_{pe}$, resulting in $\boldsymbol{E}\perp\boldsymbol{B}$ in the upstream and downstream regions.

- ✓ But the experimental results showed that E_{sta} does NOT balance E_{ind} to cancel $E_{//}$ particularly in the downstream region. Thus the plasma behavior, or, energy conversion process would be largely modified.

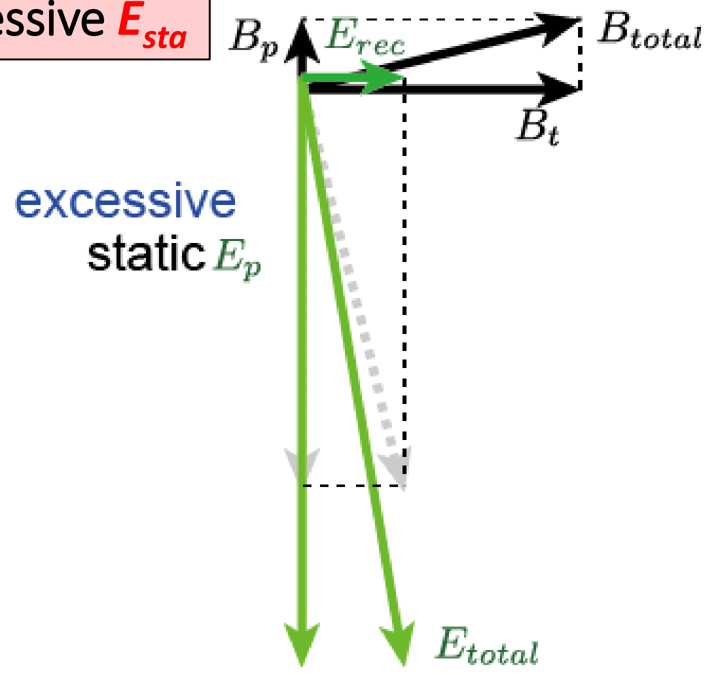


Two possible imbalanced cases

A) Insufficient E_{sta}



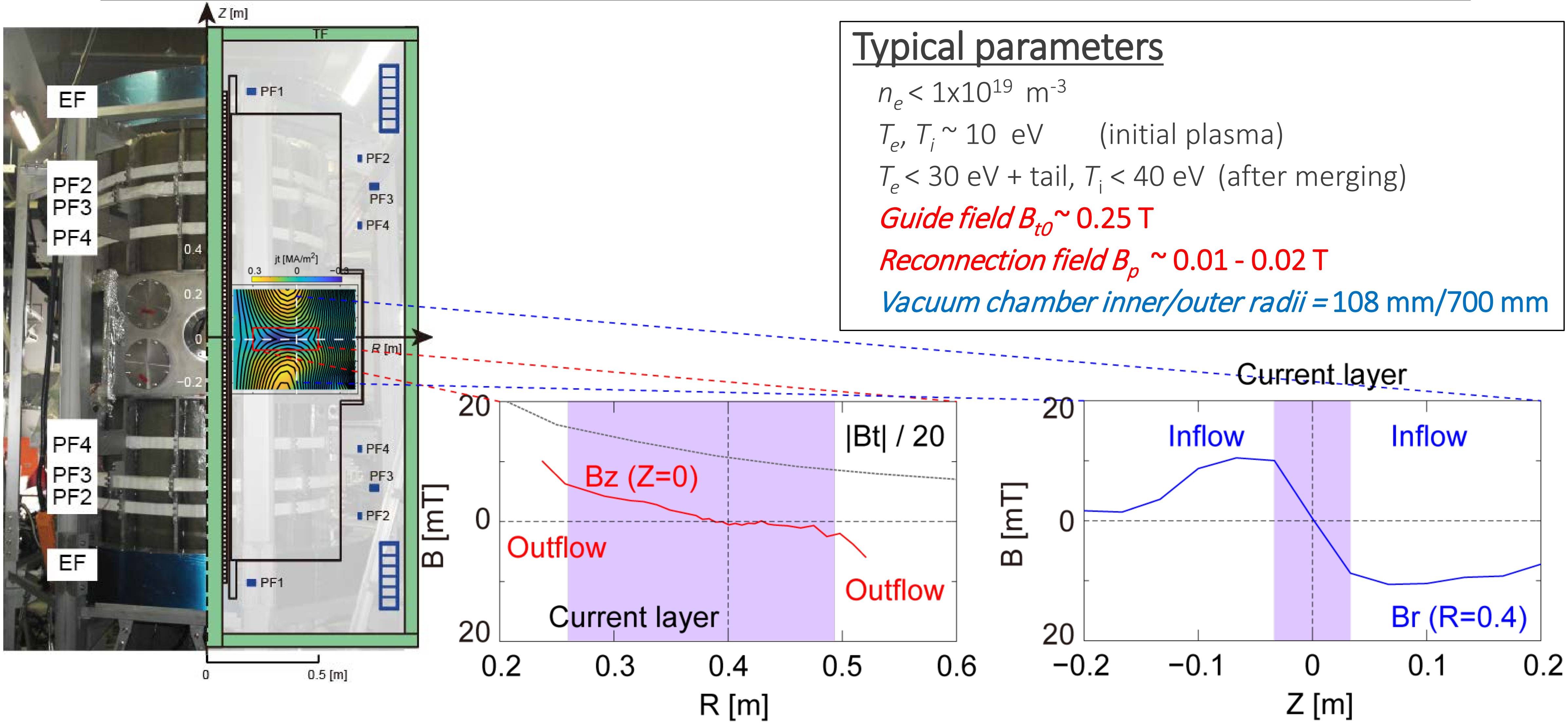
B) Excessive E_{sta}



- $E_{//}$ survives
  → parallel acceleration of charged particles
- $E_{\perp}$ is suppressed
  → ExB drift velocity decreased

- $E_{//}$ is reversed
  → quick reversal of reconnection current
- $E_{\perp}$ is enhanced
  → ExB drift velocity increased

Features of UTST experiment



Typical parameters

- $n_e < 1\text{x}10^{19}$ m^{-3}
- T_e, T_i ~ 10 eV (initial plasma)
- T_e < 30 eV + tail, T_i < 40 eV (after merging)
- *Guide field* B_{t0} ~ 0.25 T
- *Reconnection field* B_p ~ 0.01 - 0.02 T
- *Vacuum chamber inner/outer radii* = 108 mm/700 mm

Macroscopic conditions : summary

(A) Geometry :

- Axisymmetry ($\partial/\partial\theta$)

(B) Source of magnetic fields :

- Reconnecting field : produced mostly by plasma current
- Guide field : produced mostly coil current

➡ ✓ **Out-of-plane *E* is inductive**
✓ **In-plane *E* is mostly electrostatic**

(C) Boundary : vacuum chamber serves as...

- Particle boundary ($n_{e,i}\big|_{\text{@wall}} = 0$)
- Magnetic boundary (azimuthally connected conductor as a flux conserver)

  $\because$ resistive decay time $\gg$ reconnection period
- Electric boundary (controlled in this experiment)

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- Plasma current profile

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Spontaneously-generated E_{sta}

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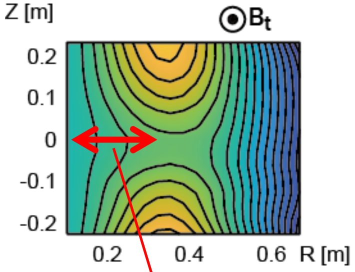
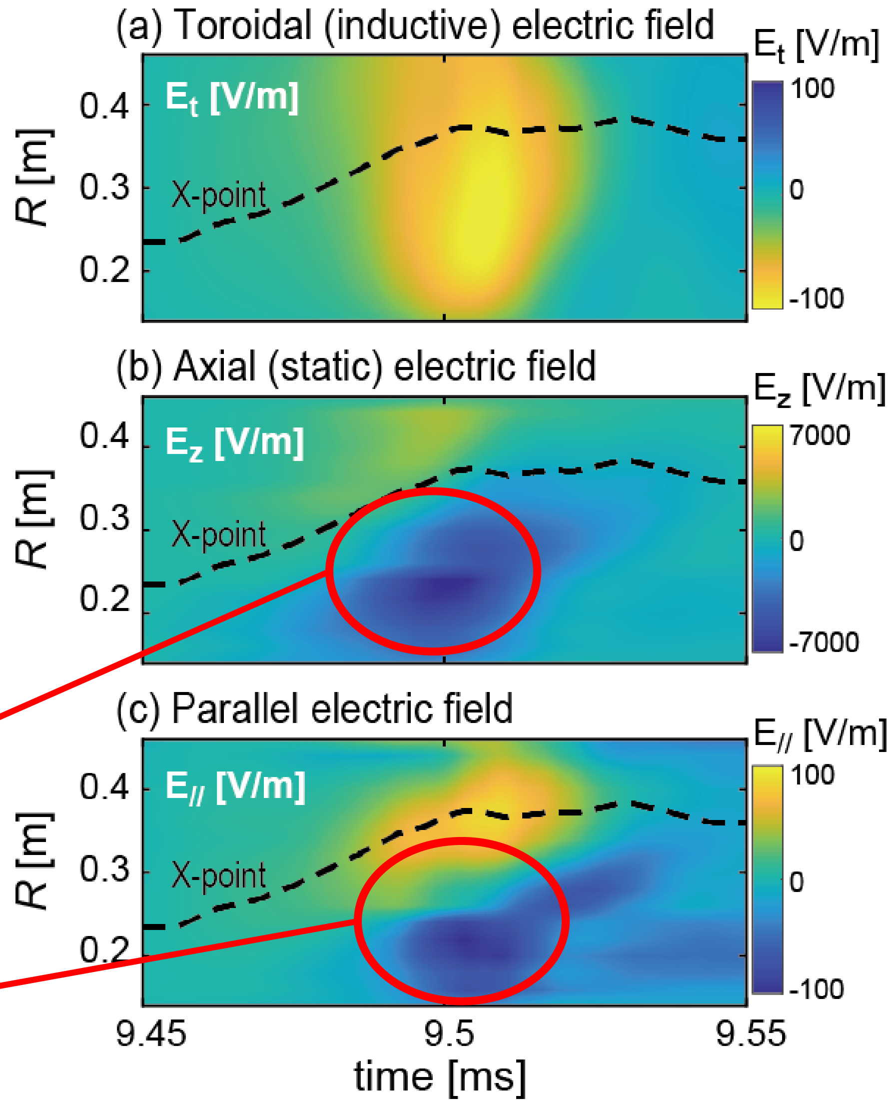
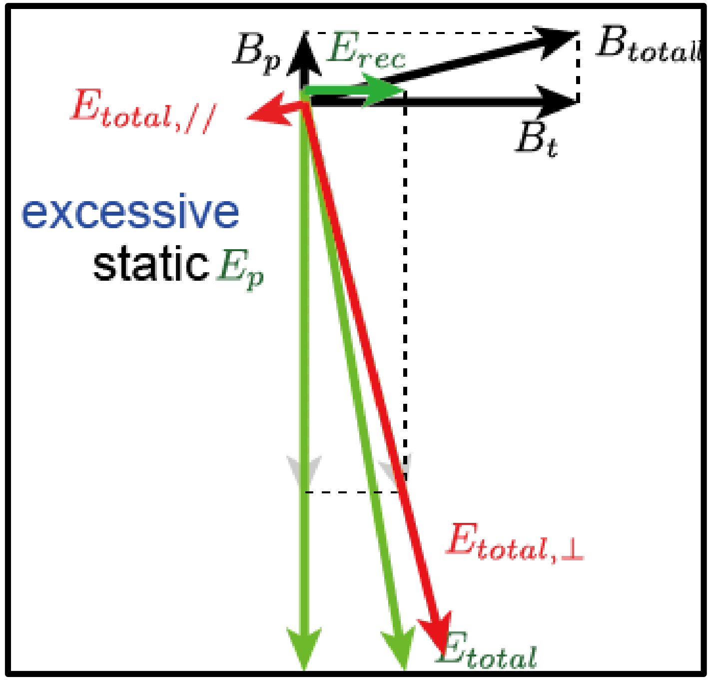


E measurement region
(Z=0, 0.14<R<0.35 m)

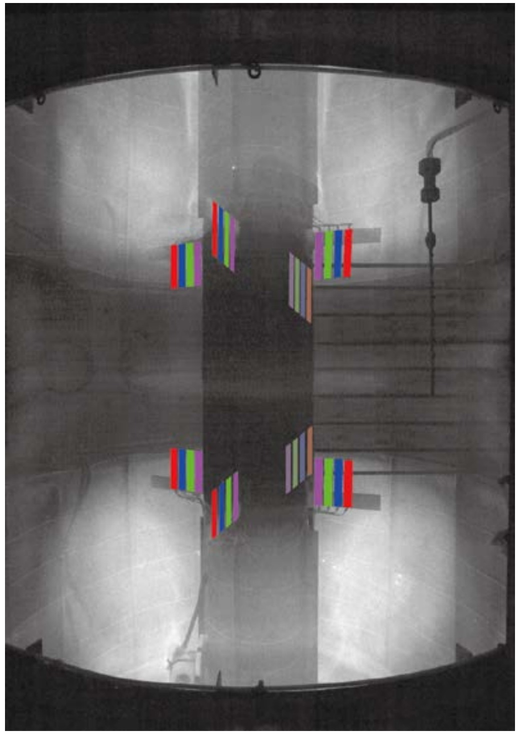


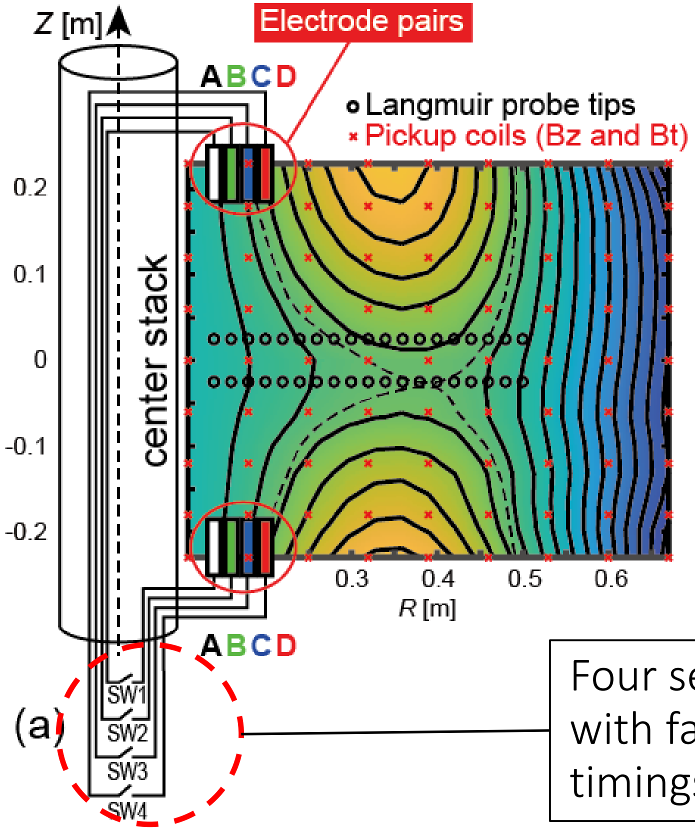


Surprisingly, self-generated $E_{z,sta}$ in the downstream region is much larger than that cancels parallel component of E_t, resulting in $E_{//}$ reversal. Why?

Electrode to observe/control electrostatic potential

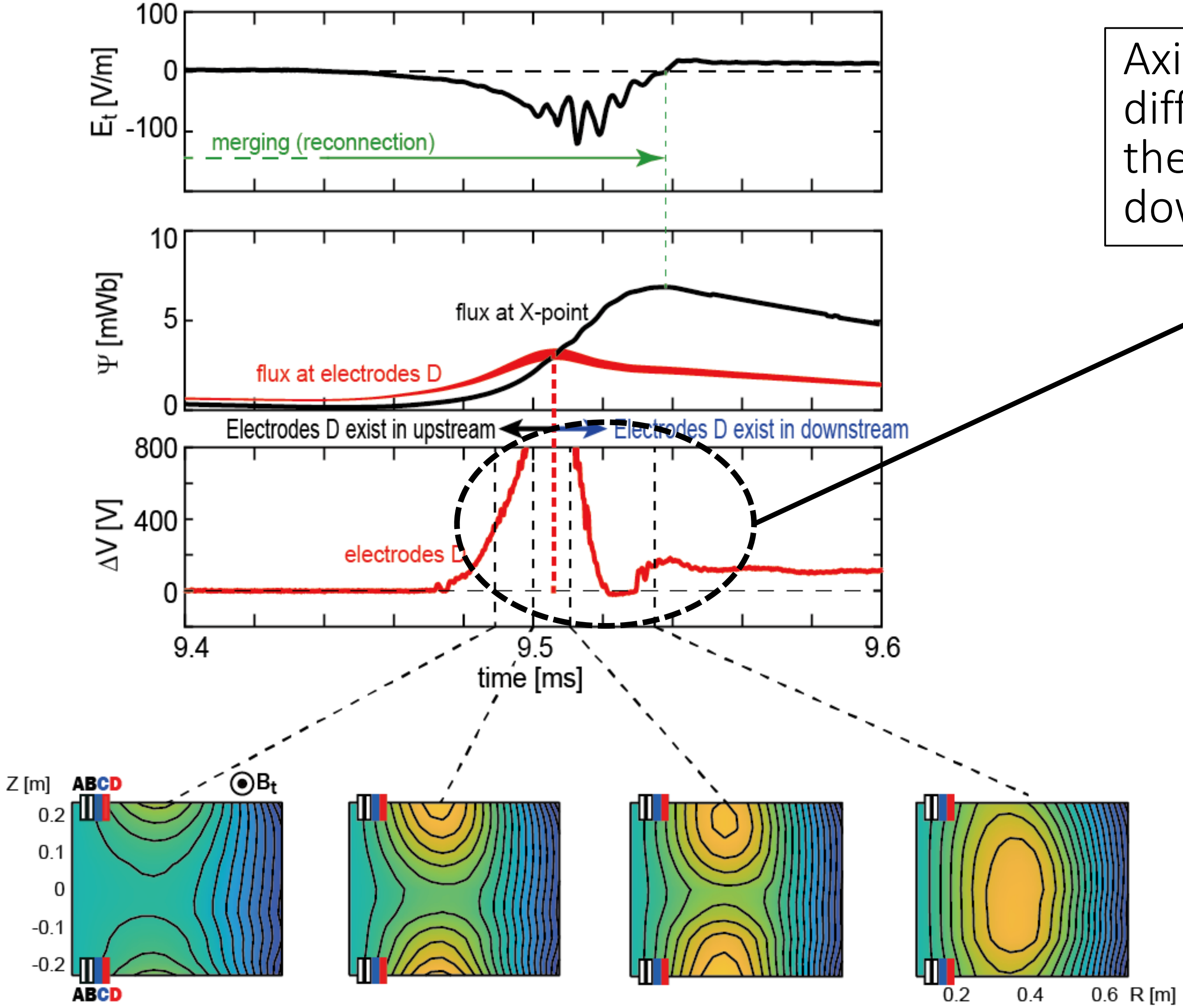
✓ Four pairs of electrodes are installed in the inboard-side downstream region to observe and to control the electrostatic potential difference. Connection between upper and lower electrodes is actively controlled.





Four separate circuits were manufactured with fast IGBT switches. Turn-on/off timings are independently programmed.

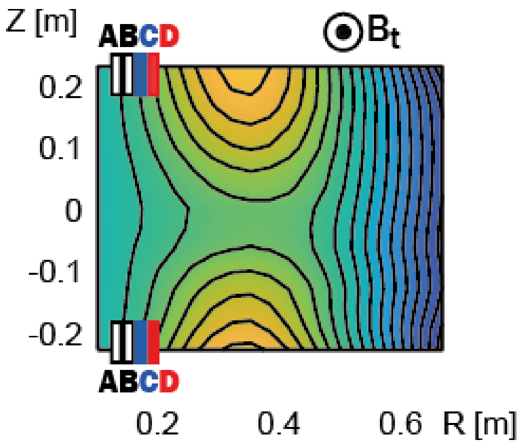
Growth in potential difference between electrode

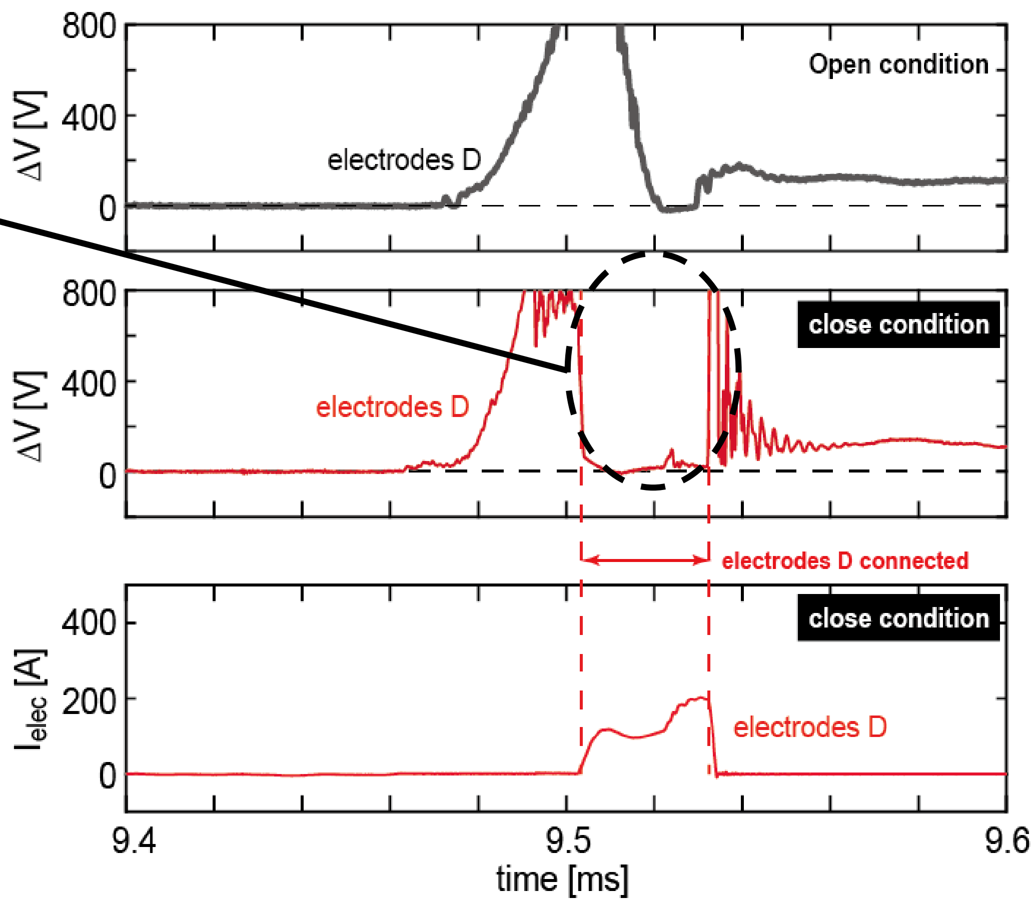


Axial potential difference grew both in the upstream and downstream regions.

Change in Boundary Condition

Electrodes D was connected (closed condition) when they are in downstream region.





The potential difference (ΔV) between electrodes was mostly disappeared by the short-circuit operation.

Artificially-controlled E_{sta}

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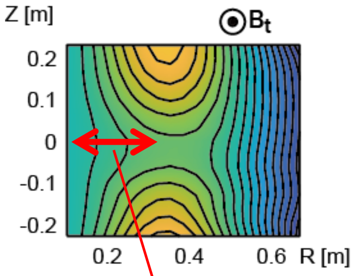
Spontaneously-generated case



E measurement region
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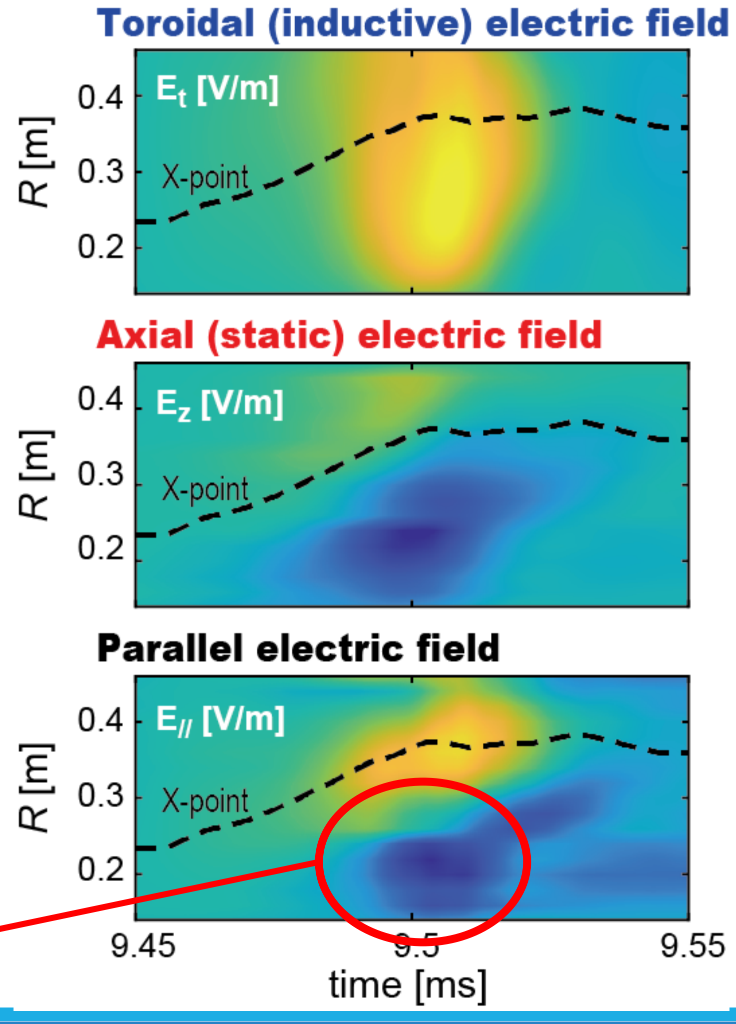
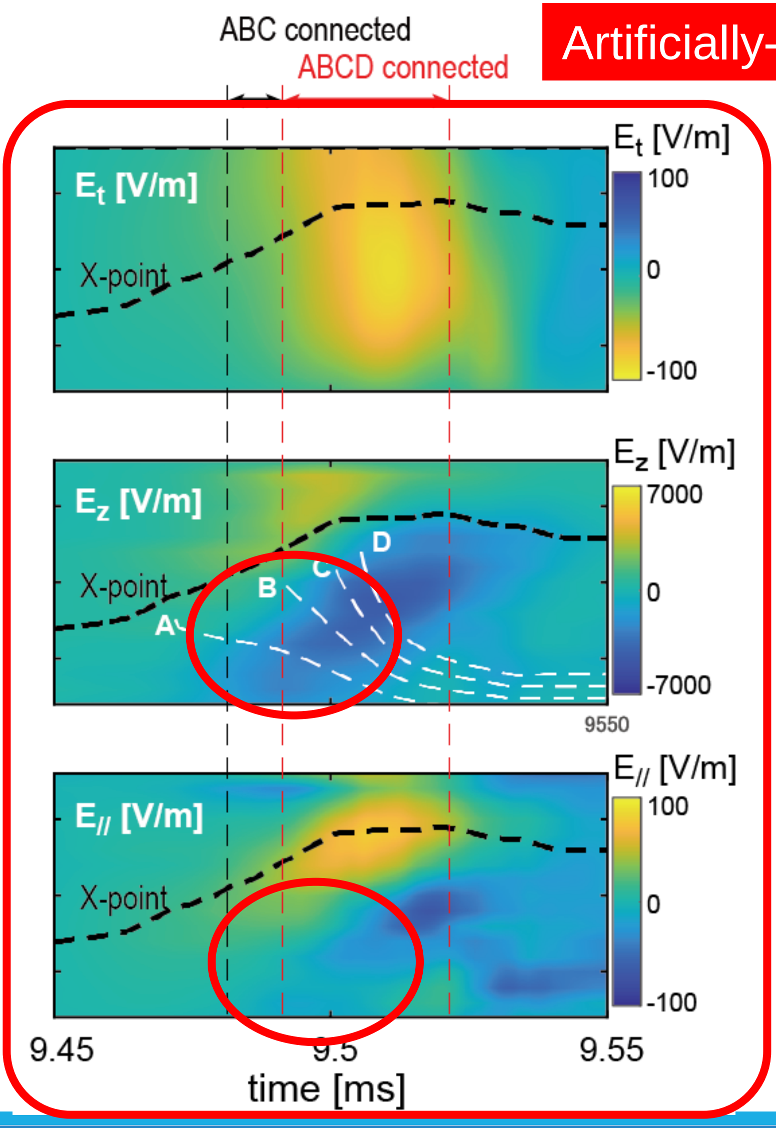
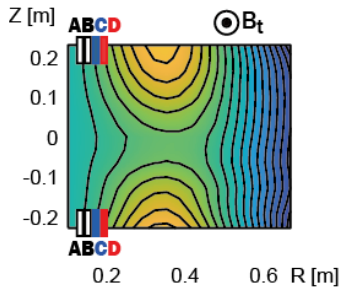


Large "reversed" $E_{//}$

Artificially-controlled case





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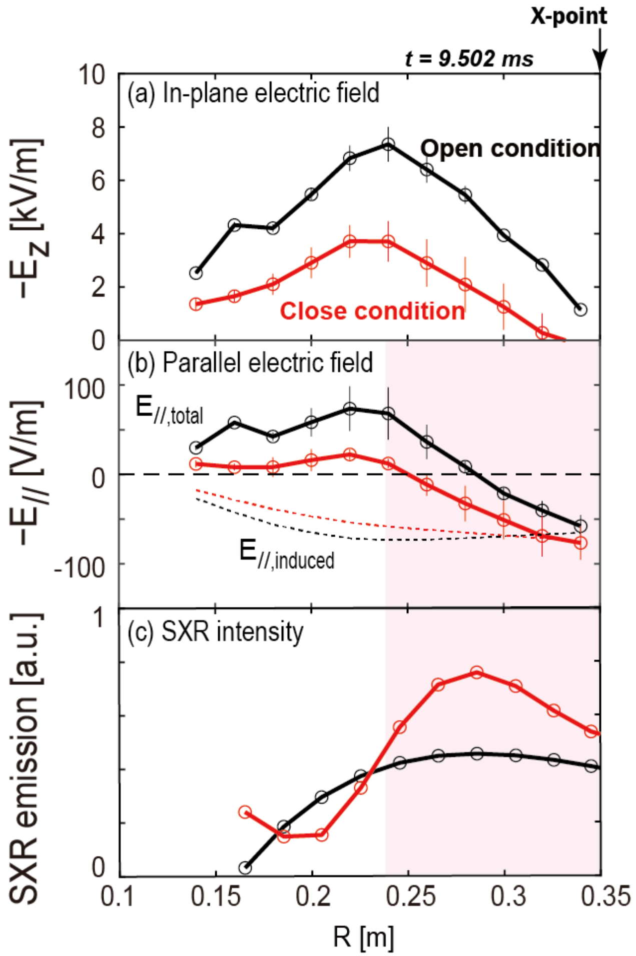
Effect of E_{sta} : (1) Particle acceleration

✓ Suppression of E_{sta} brings about an increase in $E_{//}$ near the current layer, resulting in an enhancement of SXR emission.

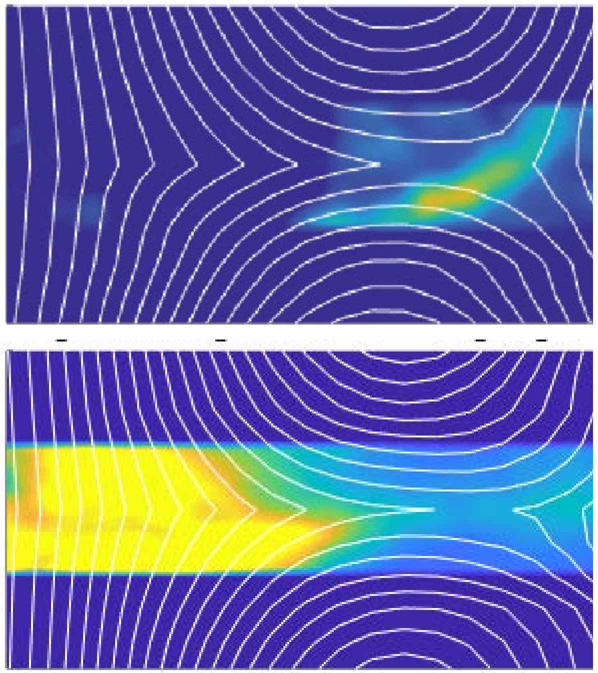


More drastic effect by large conductor

SXR emission

w/o inboard conductor plate

with inboard conductor plate



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Effect of E_{sta} : (2) Outflow velocity

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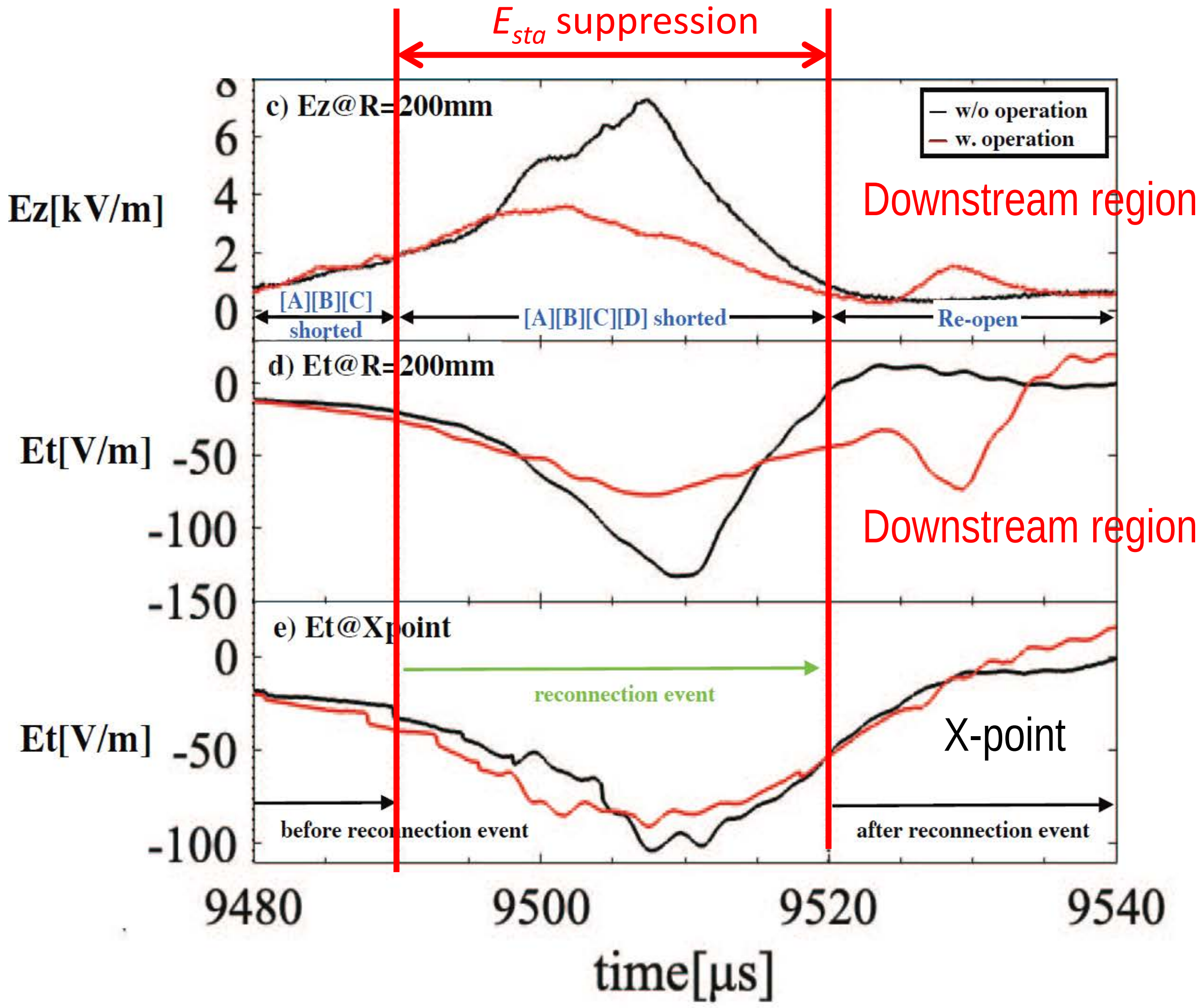

✓ Suppression of E_{sta} also slows down the field line motion in the downstream region.

These results (1) and (2) qualitatively suggest that the partition of perpendicular and parallel flow energies could be controlled by E_{sta} in high GF reconnection.

Effect of E_{sta} : (3) Current reversal

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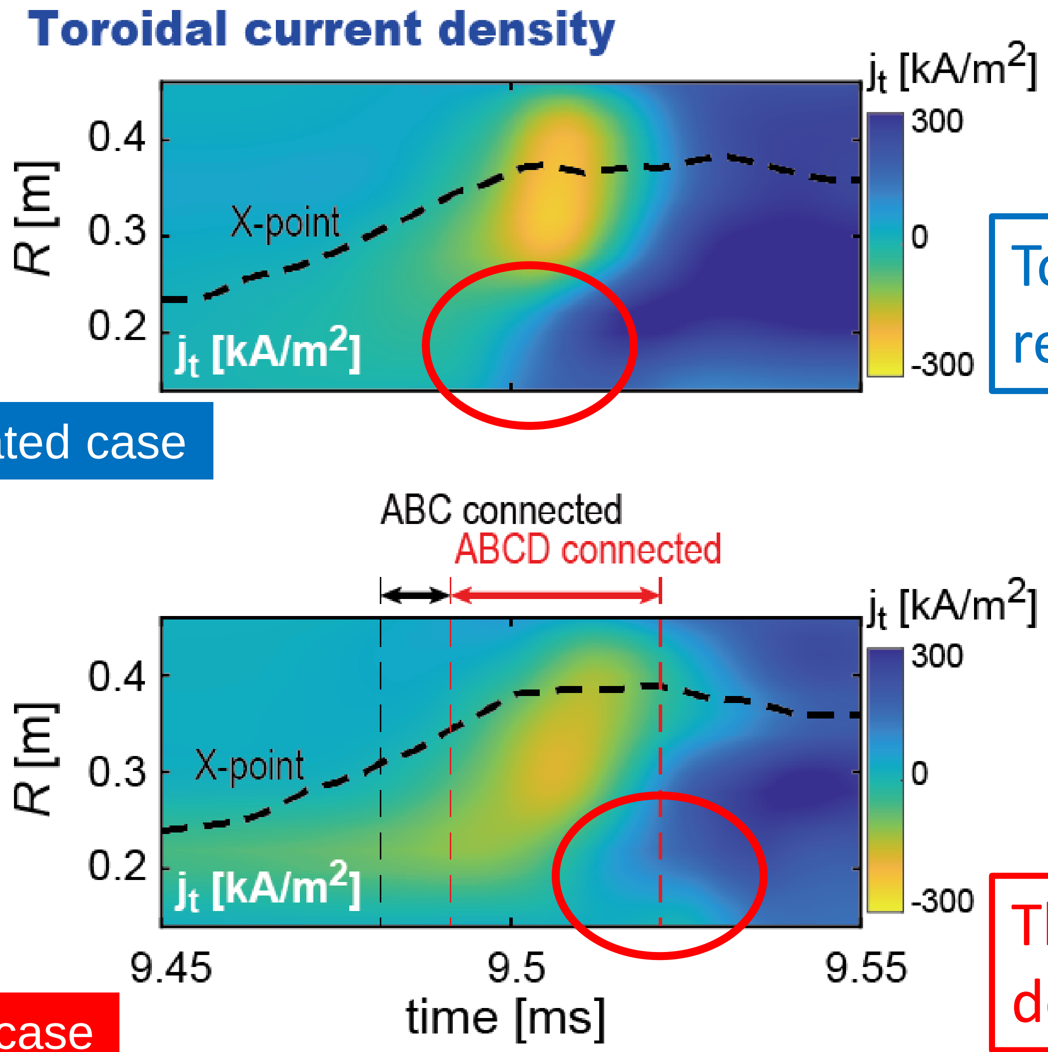


Toroidal current density was quickly reversed in the downstream region.

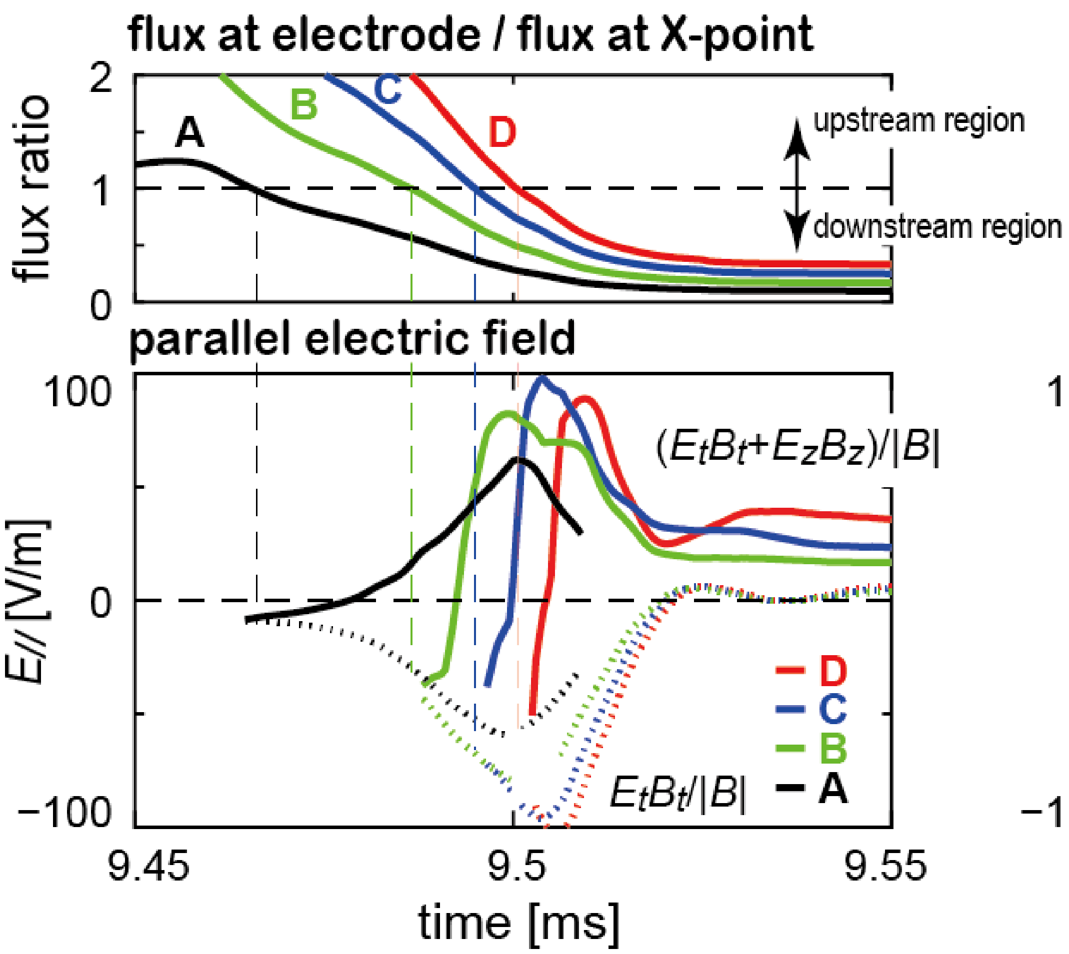
Spontaneously-generated case

The current reversal was significantly delayed in E_{sta} suppression case

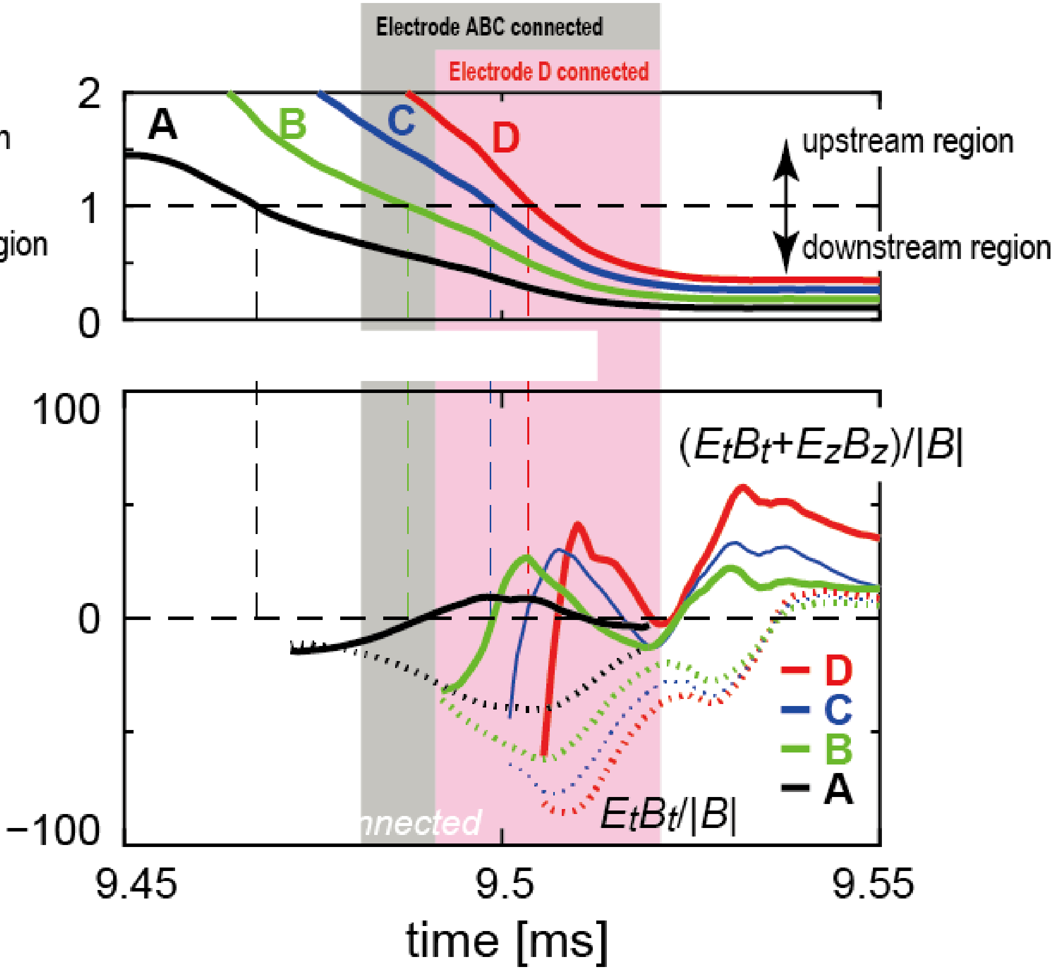
Artificially-controlled case

$E_{total,//}$ and $E_{ind,//}$ are anti-parallel

Spontaneously-generated case

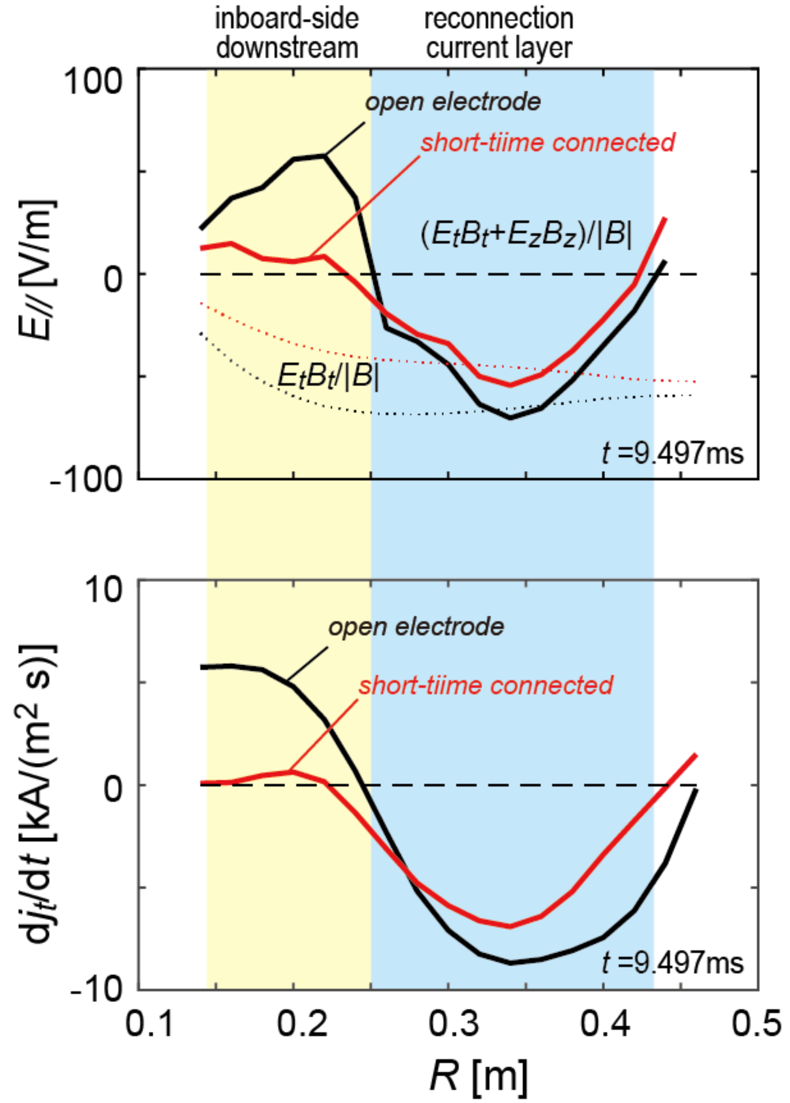


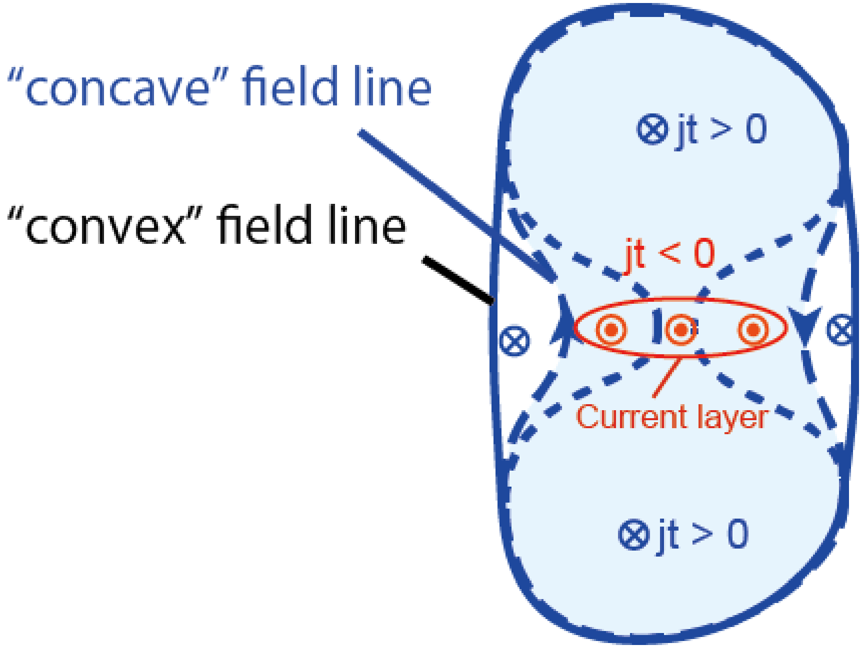
Artificially-controlled case



Large E_{sta} makes $E_{total,//}$ reversed from $E_{ind,//}$.

Effect of E_{sta} : (3) Current reversal





✓ The charged particles will move along the field lines and thus the toroidal current density will respond to the parallel electric field $\boldsymbol{E_{//}}$, not to the inductive toroidal electric field $\boldsymbol{E_t}$.

Conclusion

- ✓ Effects of **electrostatic field E_{sta}** on high-GF reconnection have been investigated in torus plasma merging experiment with **active control of electric boundary condition.**
- ✓ Partition of perpendicular and parallel flow energies could be controlled by E_{sta} in high GF reconnection.
  - ✓ **Excessive E_{sta}** accelerates the **outflow velocity**, leading to magnetic energy conversion to ion perpendicular motion.
  - ✓ **Insufficient E_{sta}** provides **parallel acceleration of electrons** while the outflow velocity is slowed down.
- ✓ Spontaneously-generated **excessive E_{sta}** reverses parallel electric field to make a toroidal current density reversal in the downstream region, that is required for forming the closed flux surfaces of merged torus plasma.