Excitation of Large-amplitude Magnetic Fluctuation in Plasma Merging Experiment

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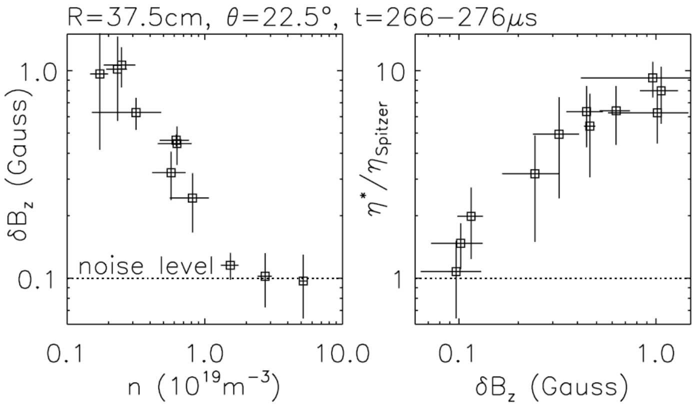
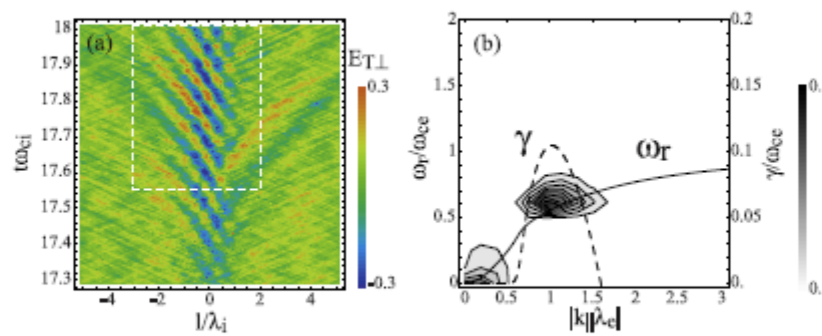
Related poster by A. Kuwahata, et al

Introduction :
Magnetic Reconnection and Waves

- **Whistler waves are often involved in collisionless Hall reconnection system in magnetosphere and laboratory experiments. Excitation of whistler waves in Hall reconnection is confirmed by numerical studies.**



MRX
(Ji, et al., PRL, 2004)



2D PIC by K. Fujimoto, GRL 2008

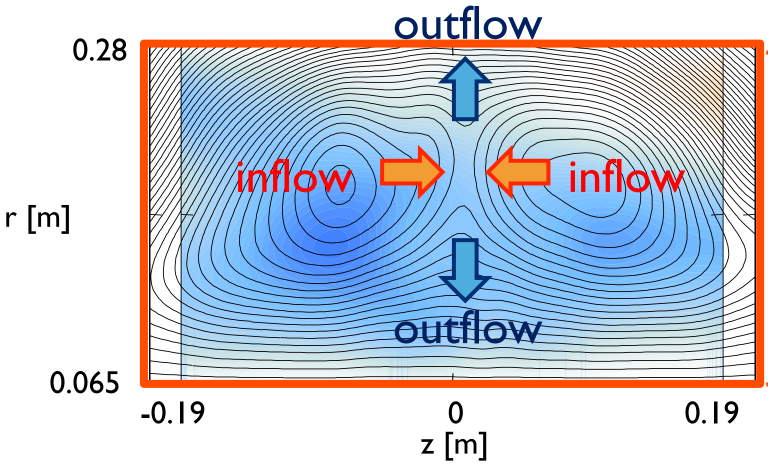
$$k\lambda_e \sim 1, \omega \sim \omega_{ce}$$

Magnetic fluctuation in lower hybrid frequency range.

- Peaks on the center of sheet (5% of reconnection field)
- Good correlation with onset of anomalous resistivity
- Broad spectrum $\omega_{ci} < \omega < \omega_{LH}$

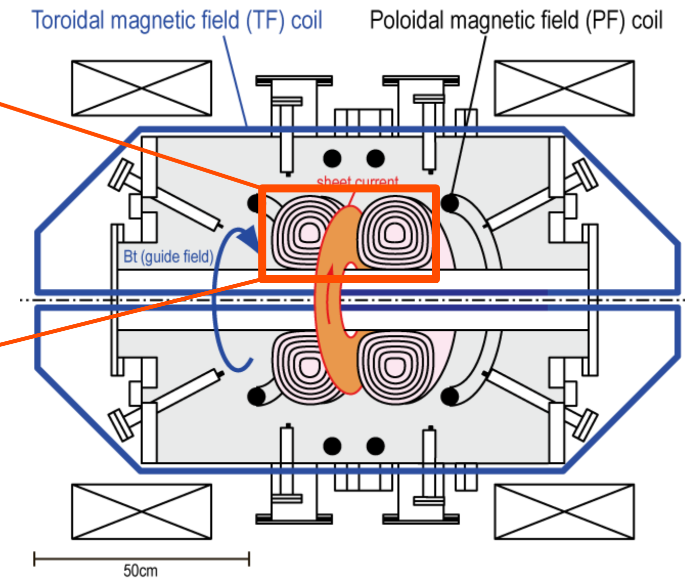
How about the reconnection case in which the Hall effect is not significant?

Fluctuation / Wave Observations in Plasma Merging Experiment (TS-3)



1MHz, 2-dim B signal (300ch)

→200MHz, dB/dt signal (48ch)



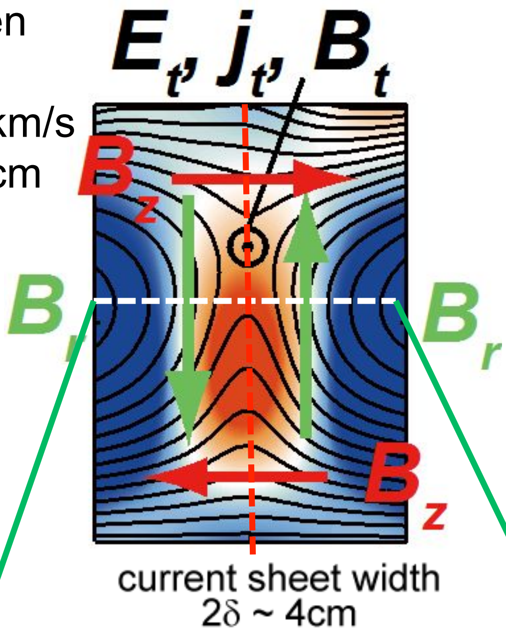
- **Large-amplitude** and **low-frequency electromagnetic waves** were detected during plasma merging under a **guide field**.

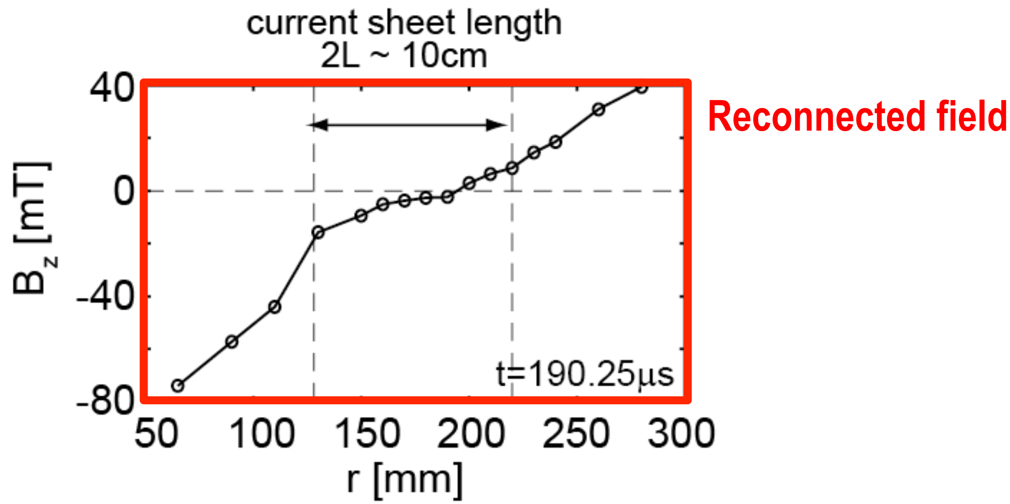
Questions:

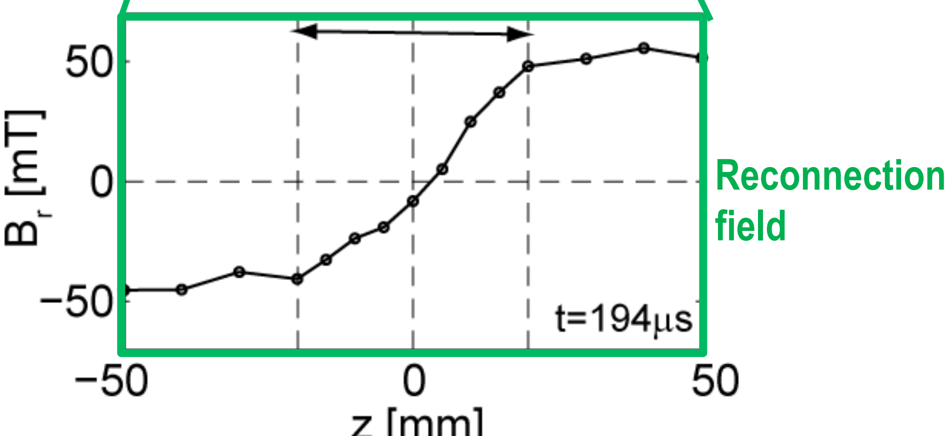
- What is the wave mode?
- How is the wave generated by reconnection?
- How does the wave affect the reconnection?

Typical Parameters of TS-3 Reconnection

Hydrogen
$\beta \sim 0.2$
$V_A \sim 100$km/s
$\lambda_{mfp} \sim 2$cm
S ~ 500

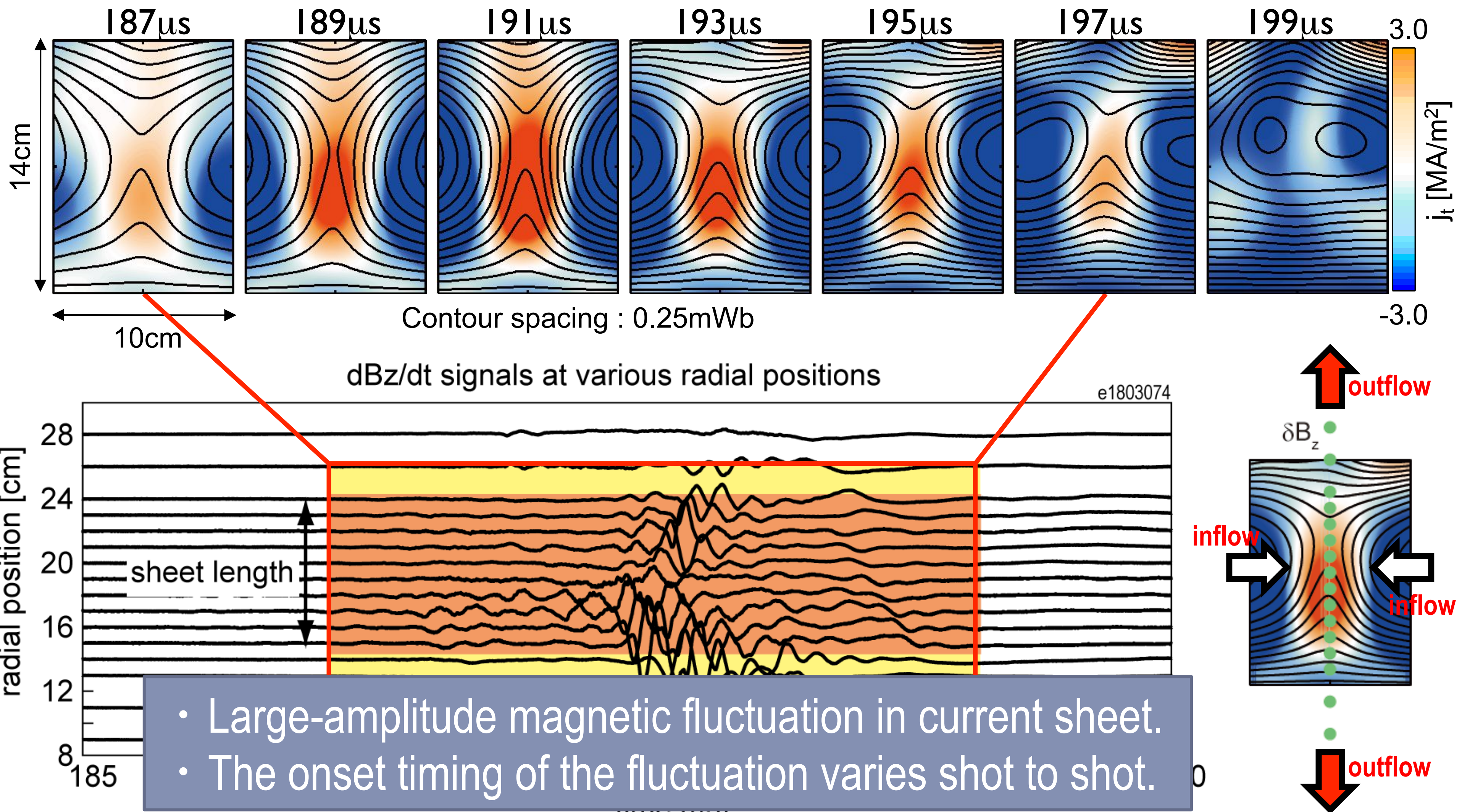






• Reconnection duration	$\tau \sim 10$ μs
• Reconnecting field	$B_r \sim 50$ mT
• Guide field	$B_t \sim 60$ mT
• Elec. density	$n_e \sim 1\times10^{20}$ m^{-3}
• Elec. / ion temperature	$T_e \sim T_i \sim 10$ eV
• Current sheet width	$2\delta \sim 4$ cm
• Current sheet length	$2L \sim 10$ cm
• Ion gyroradius	**$\rho_i \sim 0.7$ cm**
• Ion skin depth	**$c/\omega_{pi} \sim 2$ cm**
• Ion cyclotron freq.	**$f_{ci} \sim 1$MHz**
• Lower hybrid freq.	**$f_{LH} \sim 40$MHz**

Large Amplitude Magnetic Fluctuation δB_z in Reconnected Field was Observed

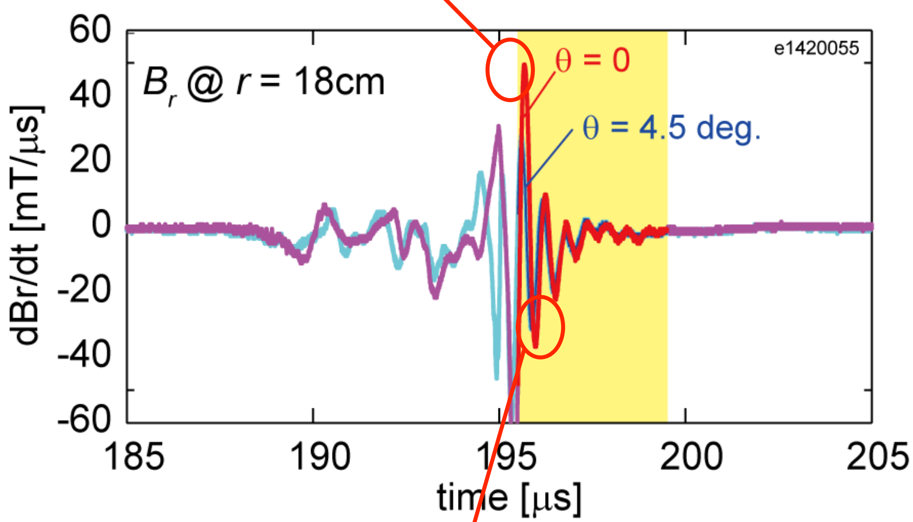


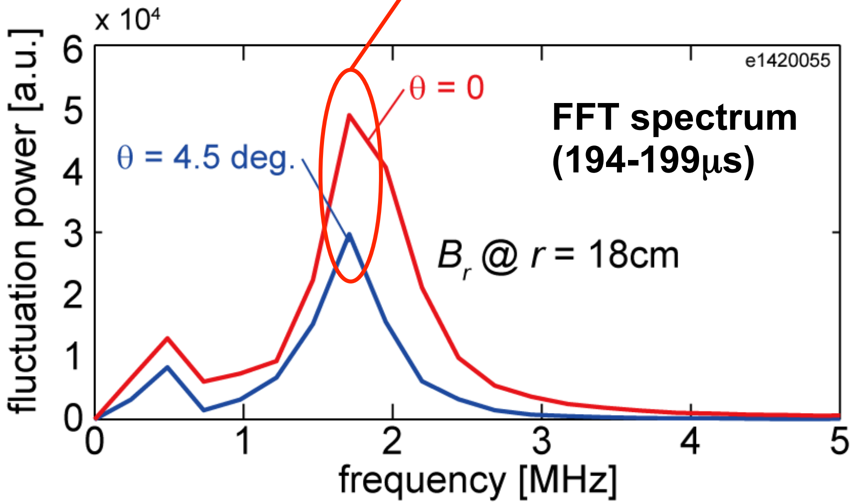
- Large-amplitude magnetic fluctuation in current sheet.
- The onset timing of the fluctuation varies shot to shot.

Features of Observed Magnetic Fluctuation

Large amplitude : the oscillation amplitude ΔB_r reaches ~10mT, up to 20% of the reconnecting field B_r.

Low frequency : FFT spectrum shows a clear peak at f=1.5 ~ 2 MHz, almost twice of the local ion cyclotron frequency (~1MHz).

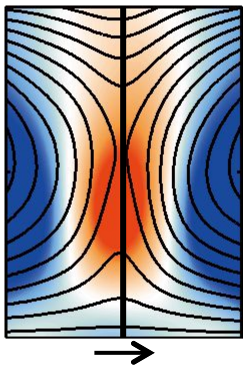




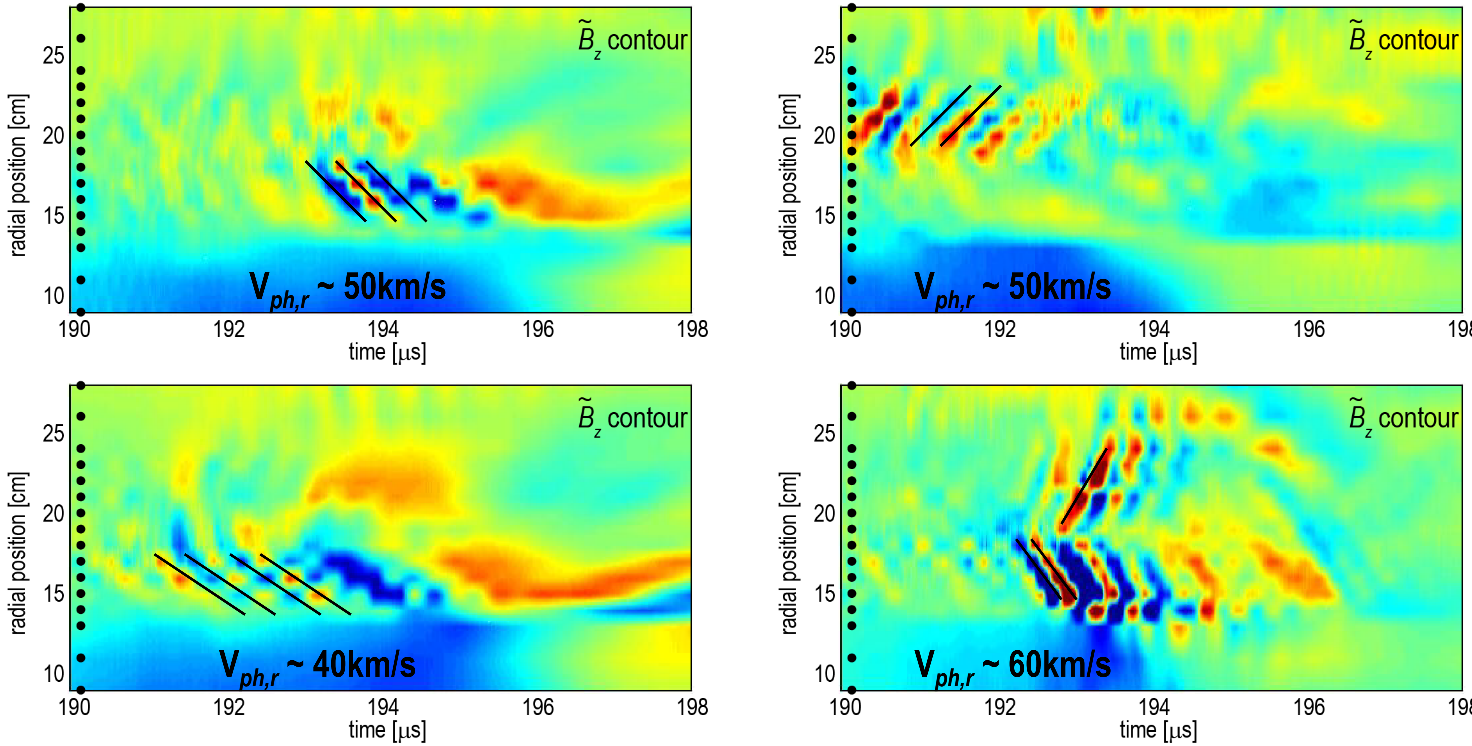
Parallel phase velocity : The magnetic fluctuation has parallel (toroidal) phase velocity of about 100 km/s, which agrees with the relative drift velocity (j_t / e n_e) in the current sheet.

Parallel wavenumber : Estimated parallel wavenumber of $\lambda_{//} \sim 7\rho_i$ ($\sim$5cm) or $k_{//}\rho_i \sim 1$.

Radial Propagation of Wave



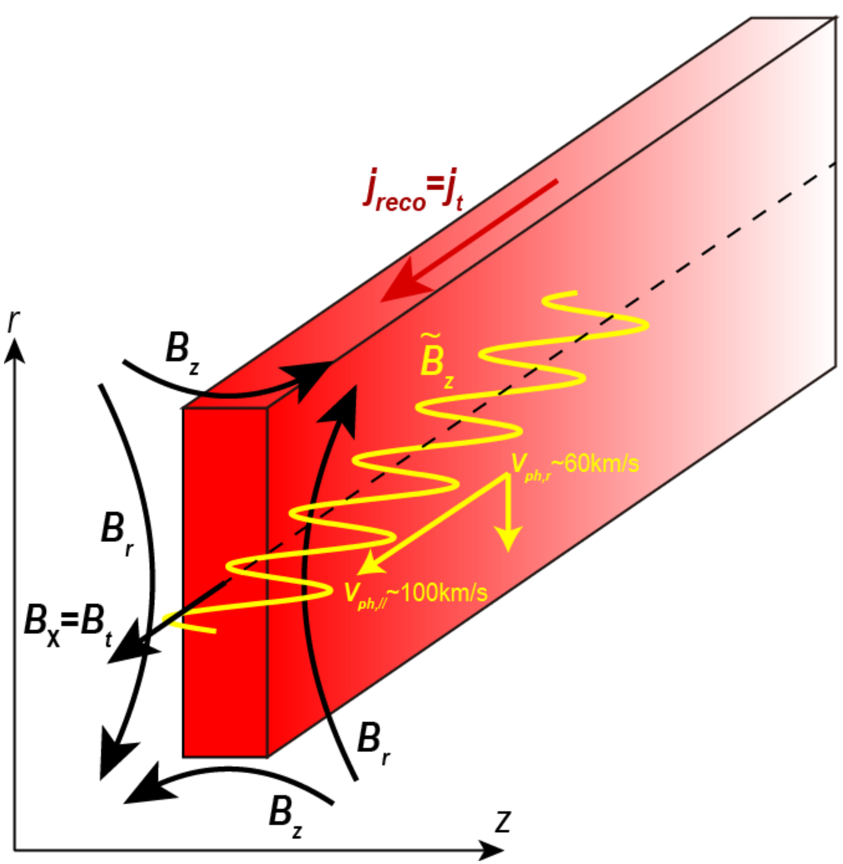
B_z : reconnected field

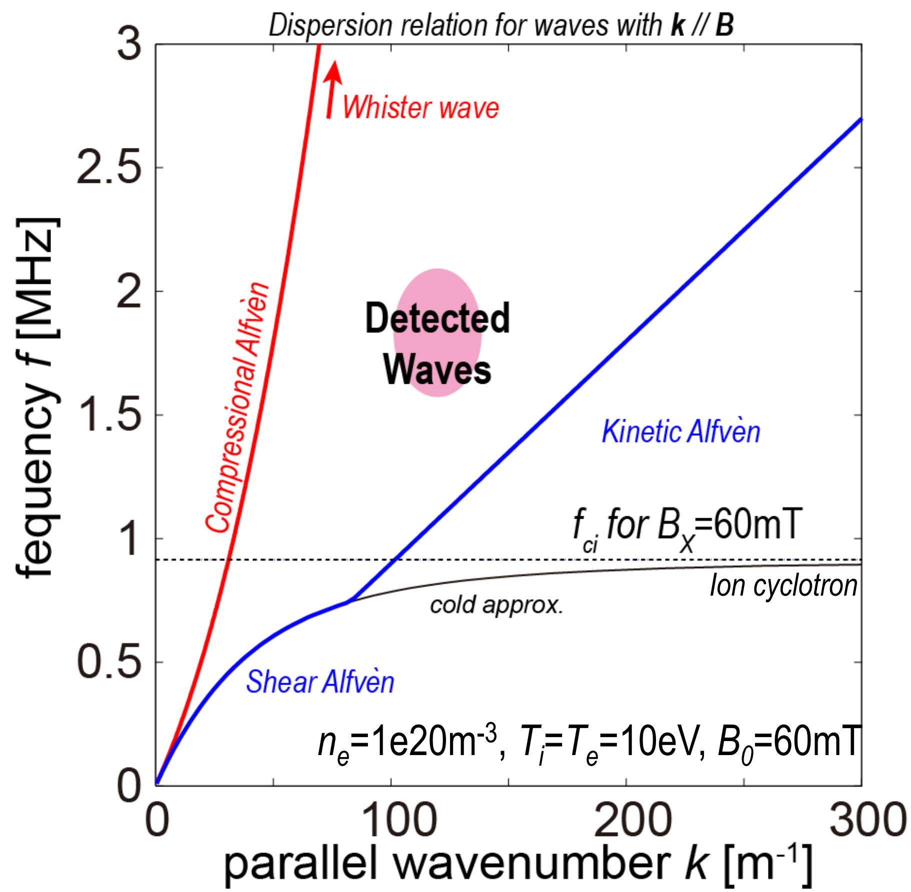


- **Radial phase velocity $V_{ph,r}$ ~ 40-60km/s : about half of the parallel phase velocity or Alfvén velocity.**
- **Discontinuity near the edge of the sheet**

Configuration of Reconnection and Wave

The observed low-frequency wave propagates near parallel to the toroidal (guide field direction) inside the current sheet.



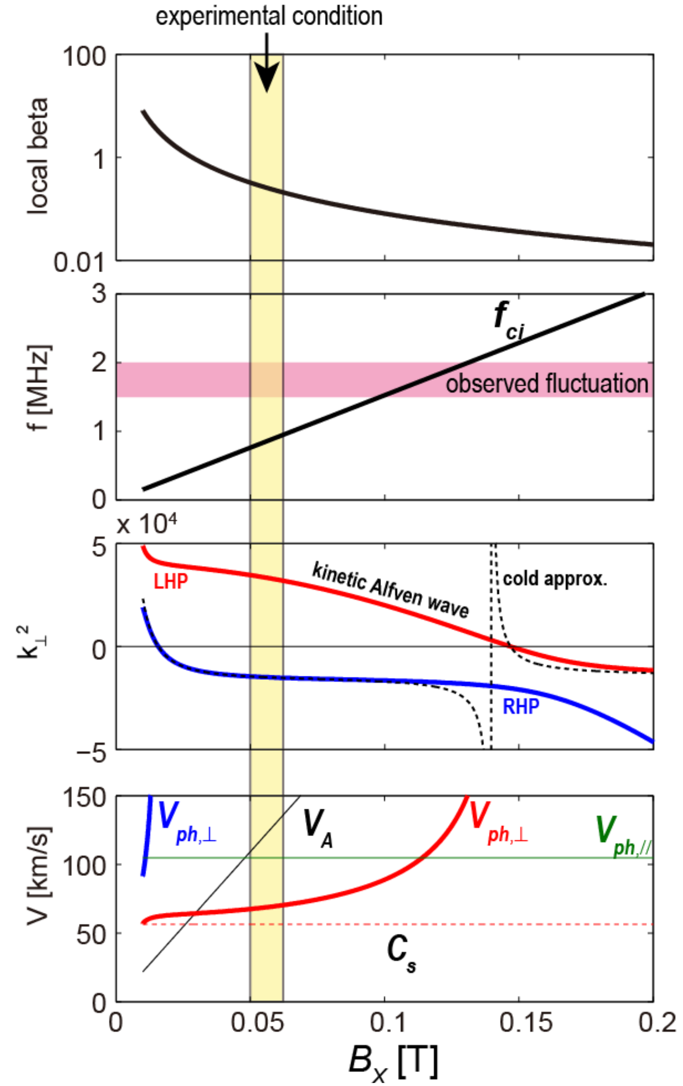


Dispersion relations of low frequency waves for various B_x

$$\left(\omega^2 - V_A^2 k_{//}^2\right)^2\left(\omega^2 + C_S^2\nabla^2\right) + \omega^2 V_A^2\left(\omega^2 - V_A^2 k_{//}^2\right)\left(\nabla^2 + k_{//}^2\right) + \left(\frac{\omega}{\omega_{ci}}\right)^2 V_A^4 k_{//}^2 \nabla^2\left(\omega^2 + C_S^2\nabla^2\right) = 0$$

Assumed experimental parameters are
- slab geometry
- $n_e = 1\times10^{20}\ m^{-3}$
- $T_e = T_i = 10$ eV
- $\gamma_e = \gamma_i = 5/3$
- $m_i = 1.67\times10^{-27}$ kg
- f = 2 MHz
- $k_{//} = 120\ m^{-1}$

Dispersion relation for fixed frequency and parallel wavenumber →

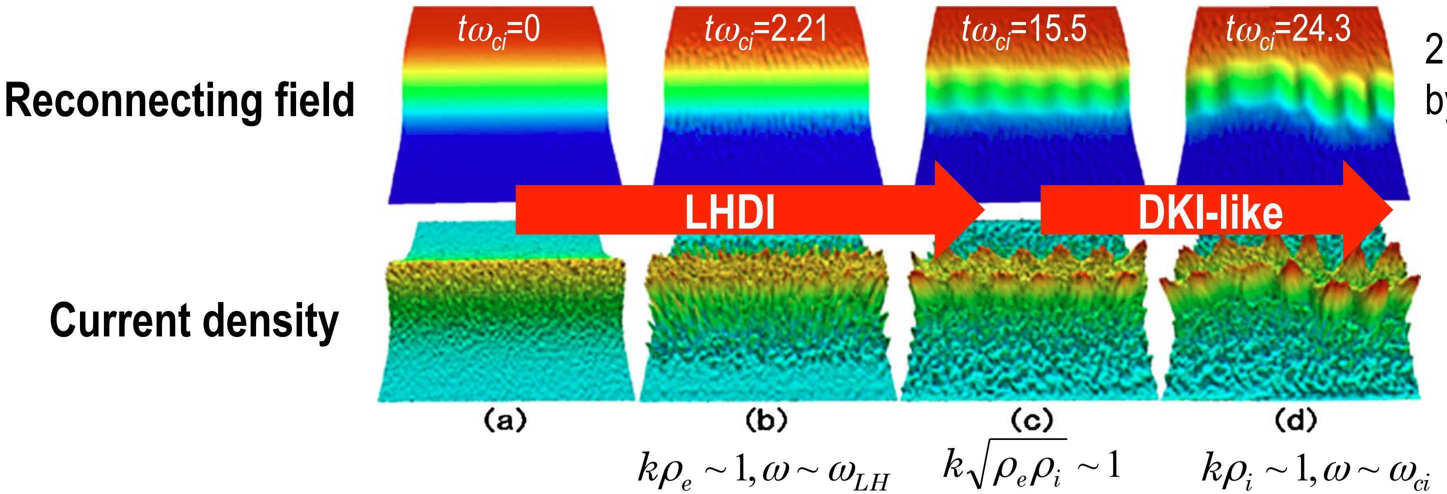


Left hand polarized wave (KAW) can propagate under the guide field of 60mT, while the right hand polarized wave (Whistler) is evanescent.

How the low-frequency wave (kinetic Alfven wave) is excited?

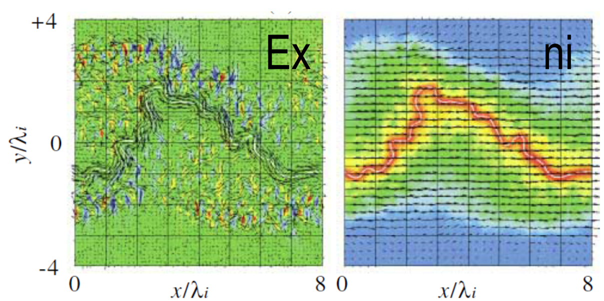
- **Longer wavelength modes induced by LHDI might couple with the low-frequency KAW with $k_{//}\rho_i \sim 1$.**

Drift-kink instability (DKI) like long-wavelength mode ($k\rho_i$~1, ω~ω_{ci})



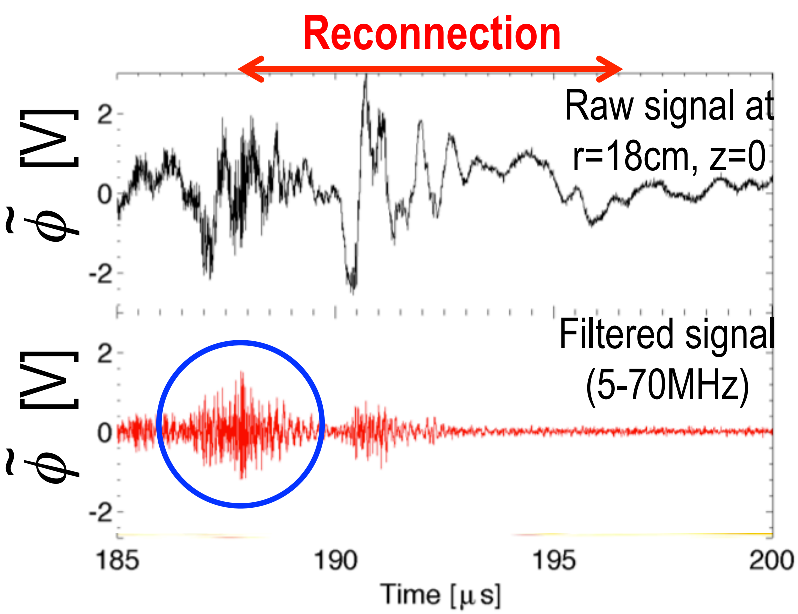
2.5D PIC (m_i/m_e=400) by Moritaka, POP 2007

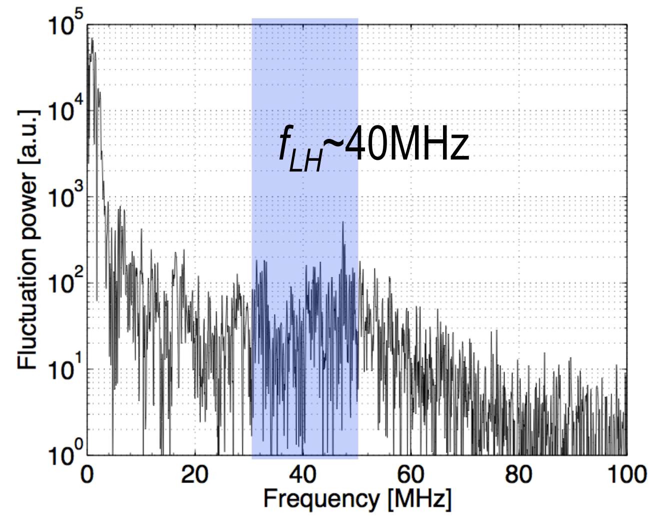
Kelvin-Helmholtz instability (λ~$8c/\omega_{pi}$)



2D PIC (m_i/m_e=400) by I. Shinohara, PRL 2001

Electrostatic fluctuation near X point





- **Higher-frequency (~ω_{LH}) electrostatic fluctuation were observed in prior to the large-amplitude magnetic fluctuation of KAW.**

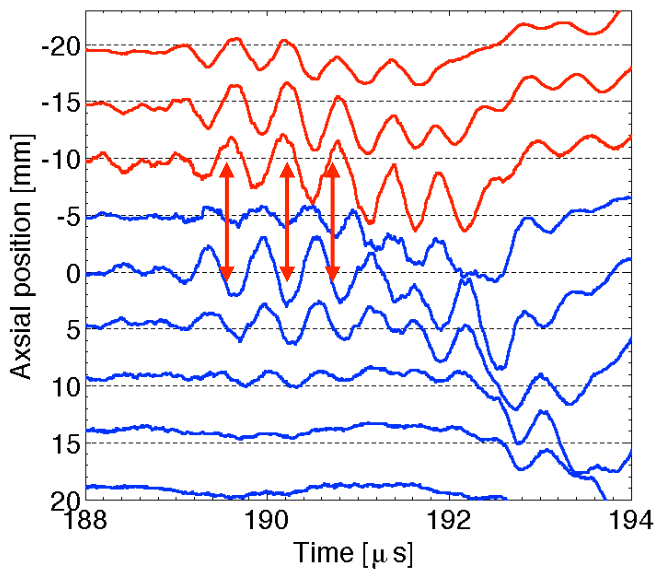
Conjectures:

- LHDI takes place in the early phase of magnetic reconnection.
- Longer-wavelength modes driven by LHDI.

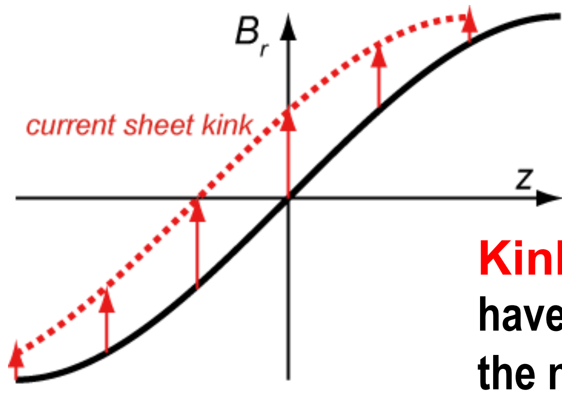
Sheet Deformation Due to Fluctuation

- **Phase of dBr/dt signals change sign across the neutral sheet.**

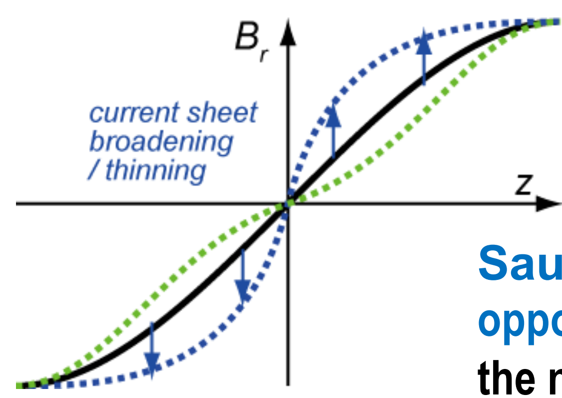
Zoom-ups of dBr/dt signals



These signals suggest that the current sheet deformation is not due to the kink mode.

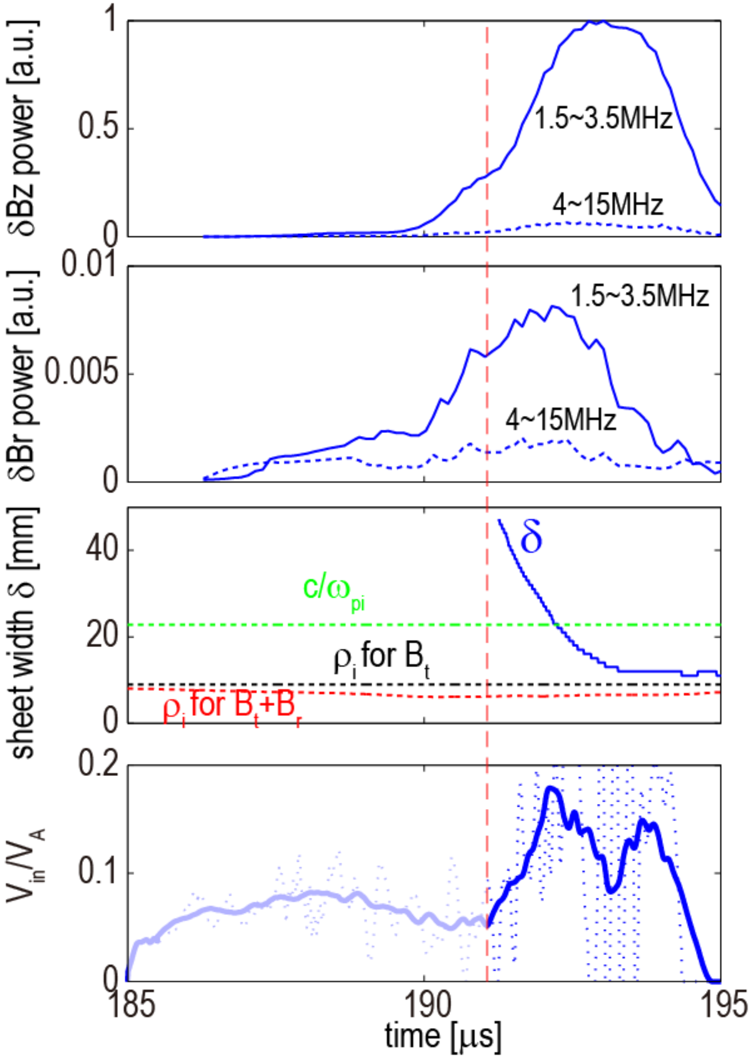


Kink → δBr should have same sign across the neutral sheet



Sausage → δBr has opposite sign across the neutral sheet (Buchner 1999)

Enhancement of Reconnection Rate

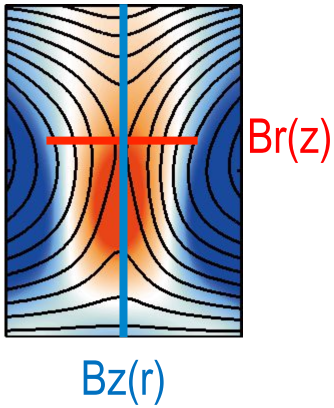


- **Enhancement of averaged reconnection rate at the same time as the onset of large-amplitude B_z fluctuation.**
- **Growth of B_r fluctuation is observed in prior to the B_z fluctuation burst.**

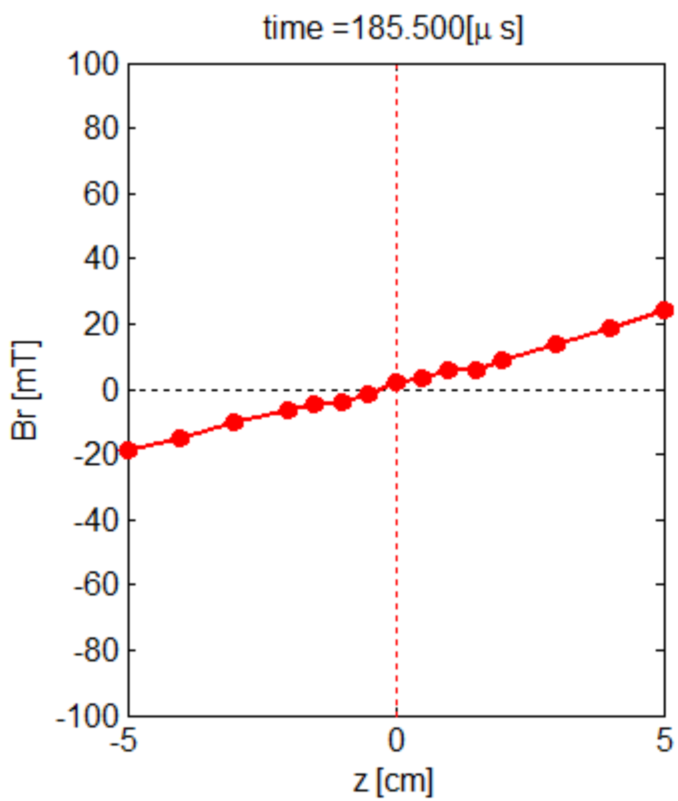
Conjecture:

- The large-amplitude B_z wave might be driven when the longer-wavelength current sheet instability couples with a wave mode such as KAW near the X point.

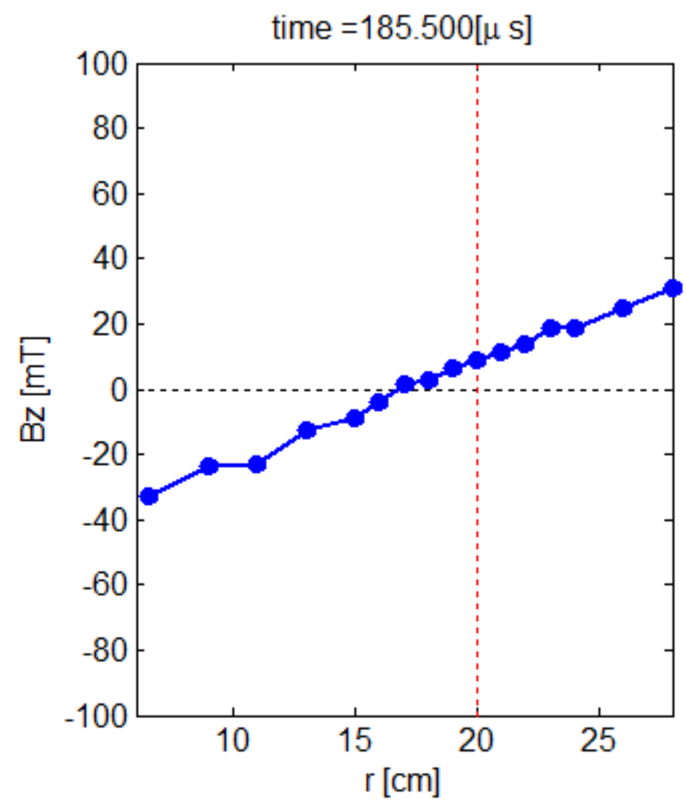
Evolution of reconnection and fluctuation



Axial profile of
Reconnection field Br
(across the current sheet)

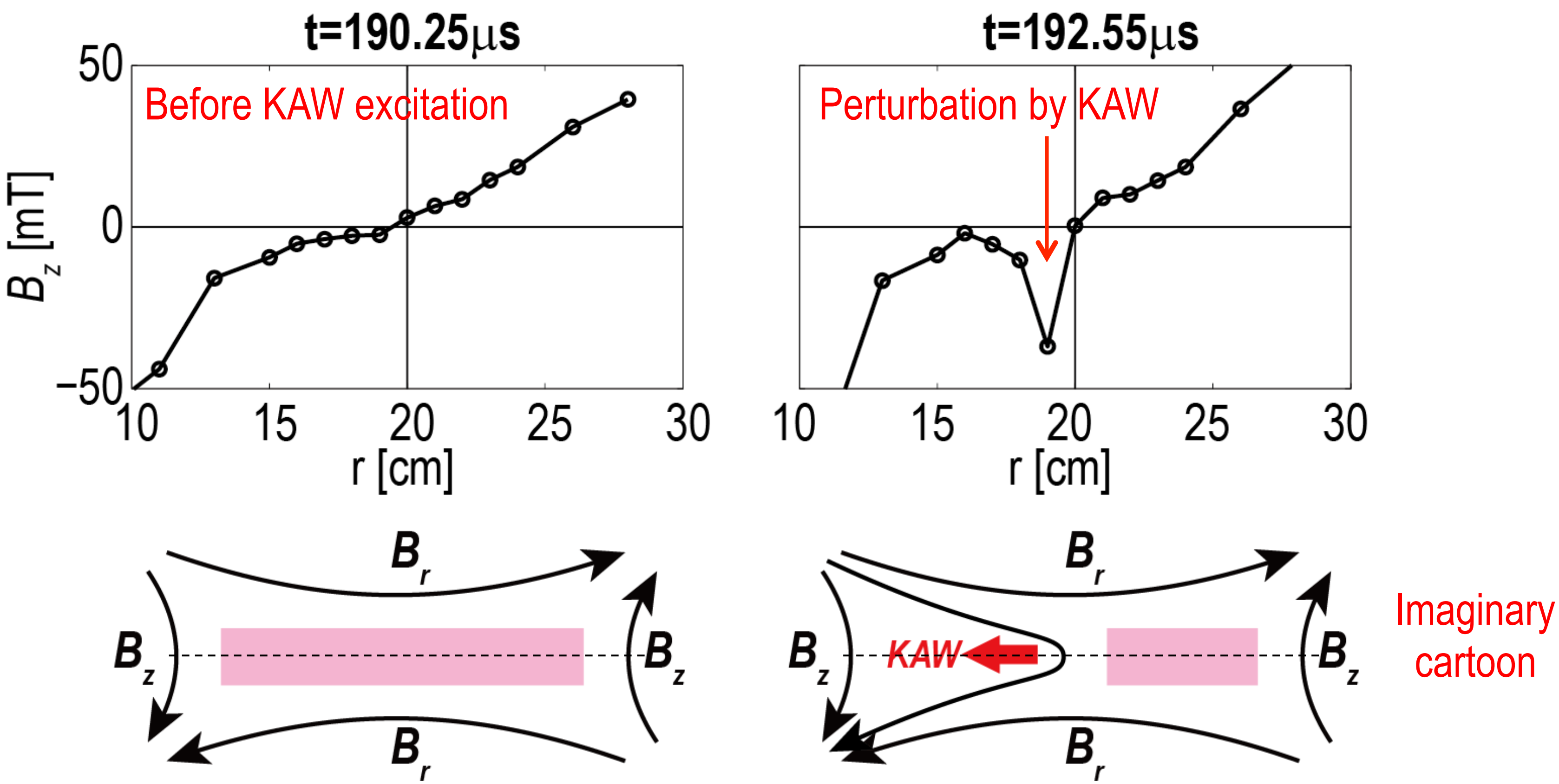


Radial profile of
Reconnected field Bz

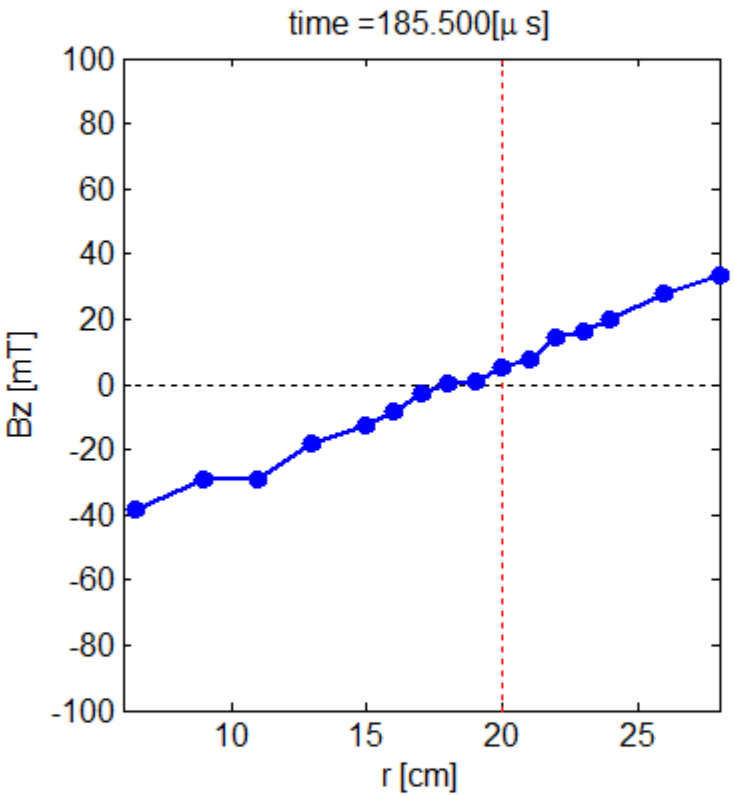


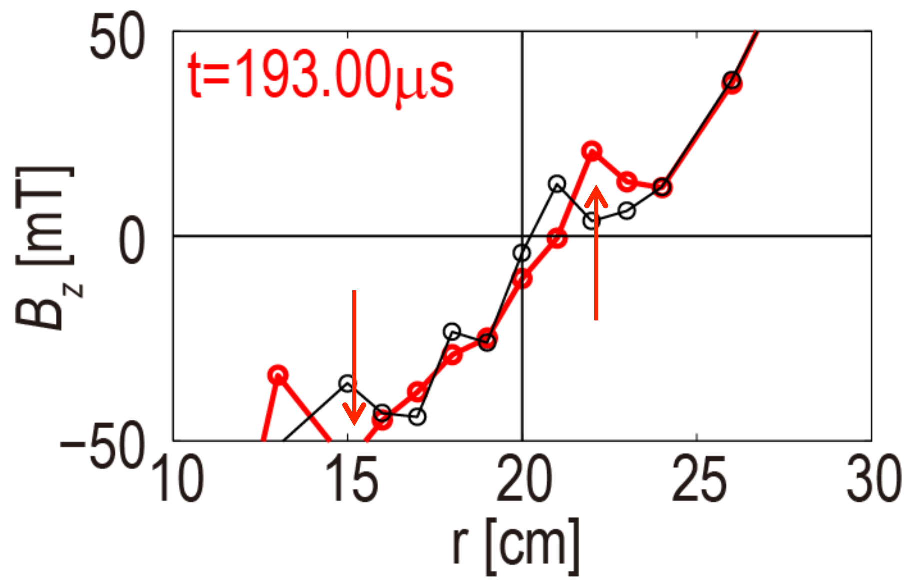
Reconnection structure modified by KAW

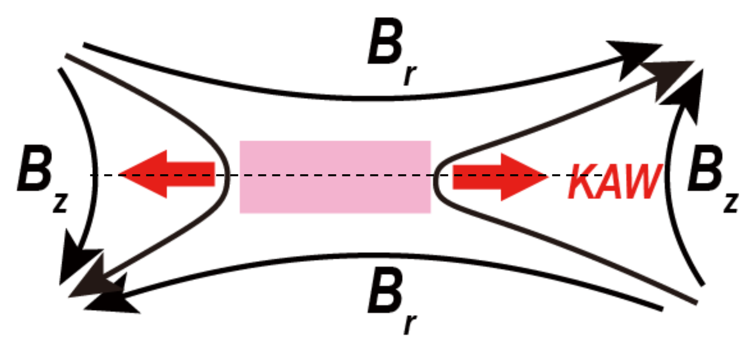
- **The KAW excited near the X-point modifies the shape of the diffusion region, maybe leading to fast reconnection.**



Bidirectional KAW propagation case







KAW could transfer the released energy into the outflow region in the original (SP like) diffusion region.

Summary

- **Large-amplitude and low-frequency electromagnetic waves during reconnection have been investigated in plasma merging experiment with a guide field.**
  - **Obliquely propagating KAW**
  - **LHDI ($\sim\omega_{LH}$) drives longer-wavelength mode ($\sim 2\omega_{ci}$)**
  - **The longer-wavelength mode couples with KAW to excite large-amplitude electromagnetic wave ($\Delta B_{//} \sim 0.2\ B_{//}$)**
  - **KAW modifies the reconnection structure to form localized diffusion region, potentially leading to intermittent fast reconnection.**