In situ evidence of firehose instability in multiple magnetic reconnection

Laboratory of Plasma Physics

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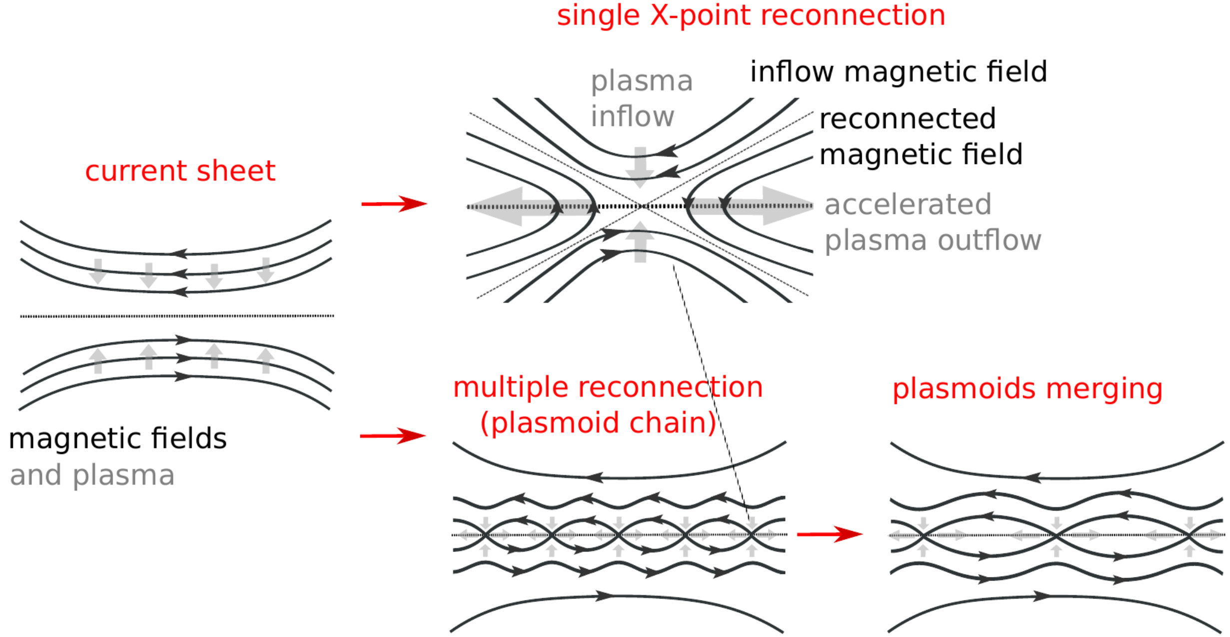
Motivation

Current sheets may disrupt into single X-line or multiple reconnection sites

Multiple reconnection → plasmoids form between the adjacent X-lines
[e.g. Bhattacharjee+2009, Markidis+2012, Uzdensky & Loureiro 2016]



? The effect of plasmoid dynamics on the large-scale energy redistribution during multiple reconnection is not yet fully understood

- From simulations: plasmoid contraction leads to the acceleration of trapped ions, ion parallel acceleration is limited by the firehose instability
[(Drake+2010 (2D PIC), Burgess+2016 (3D hybrid)]

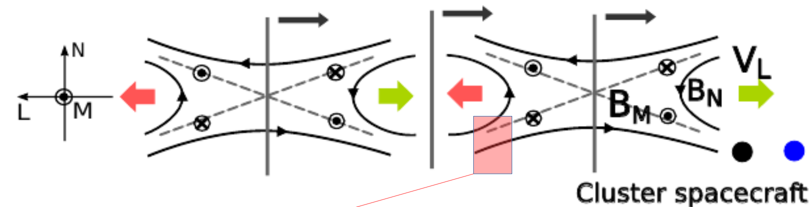
→ Goal:

- Study from direct observations the dynamics of the plasmoid formed between active X-lines and understand possible role of the ion firehose instability

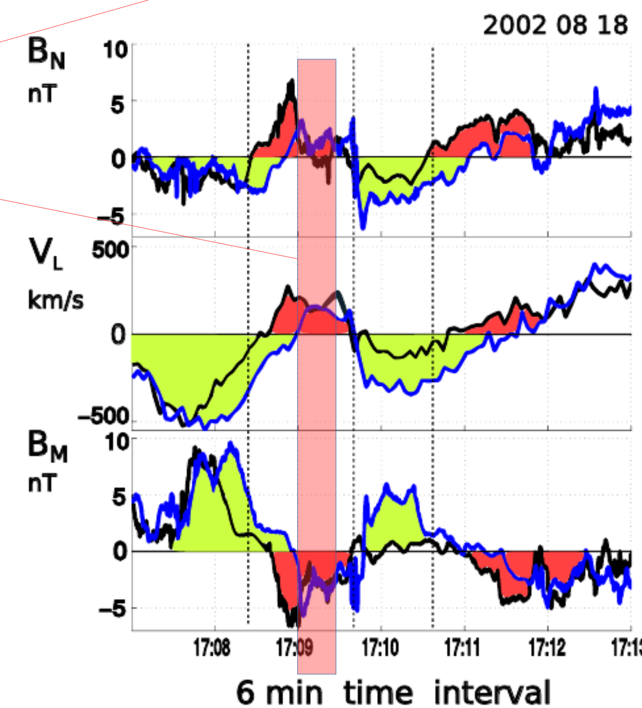
Methodology

1. Cluster spacecraft in the Earth's magnetotail

- In situ observations of multiple reconnection
  = plasmoid & neighboring X-lines
- were provided in the Earth's magnetotail [Hwang+2013; Alexandrova+2015]
- a case study: complex temporal evolution of a plasmoid between two X-lines (Cluster, 2002 August 18) [Alexandrova+2016]:
  ion-scale time changes in magnetic field topology between the X-lines



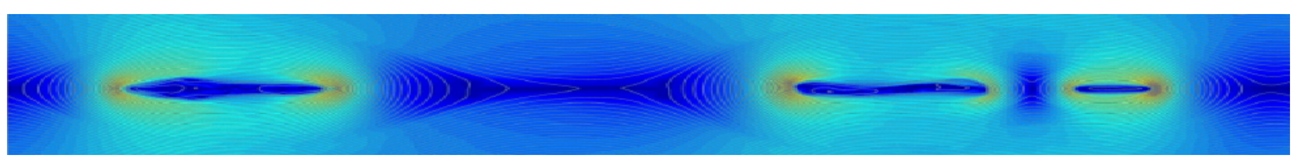
we focus here



We study 2002 August 18 event and analyze

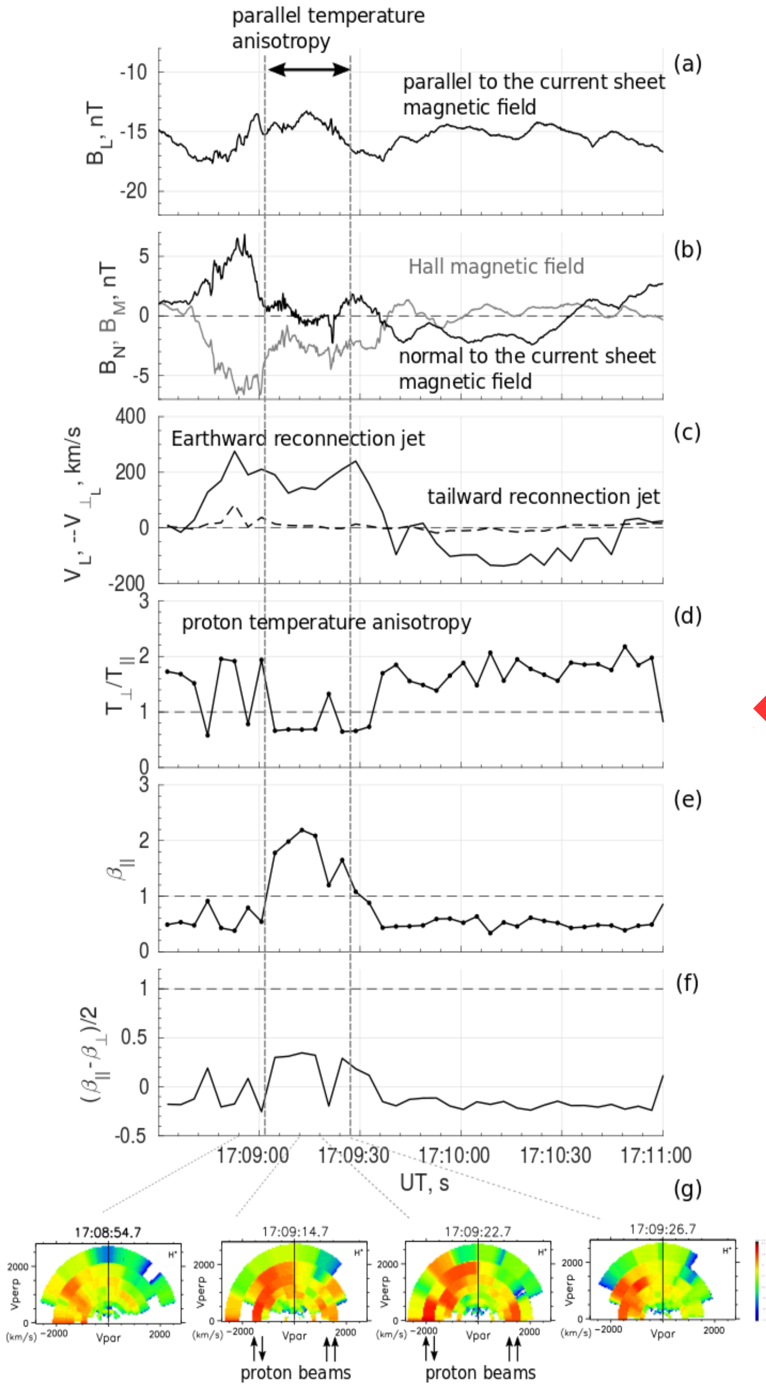
- ion distributions and temperature anisotropy
- electromagnetic fluctuations
- plasma stability

2. PIC simulations



- reconstruction of observations by 2.5D implicit particle-in-cell (A. Divin)
- allow to follow the space-time dynamics of the plasmoid

Plasmoid between two reconnection sites

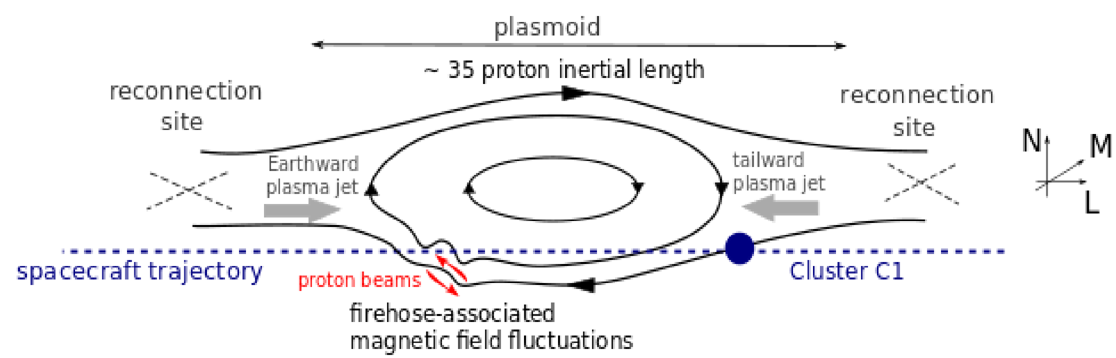


Cluster observations in the Earth's magnetotail

2002 August 18, 17:07:00-17:13:00 UT
17.7 R_E tailward and 5 R_E dawnward in GSM
Data are represented in the current sheet conventional coordinates LMN (L is parallel to the current sheet and perpendicular to the reconnection line, M is parallel to the reconnection line, N is perpendicular to the current sheet.

Calculated by MVA [Sonnerup and Cahill, 1967]
at 16:40 - 17:00 UT current sheet crossing prior to reconnection
In GSM: L = (0.99, 0.03, 0.09)
M = (0.00, 0.95, 0.31)
N = (0.10, 0.31, 0.95)

Temperature anisotropy



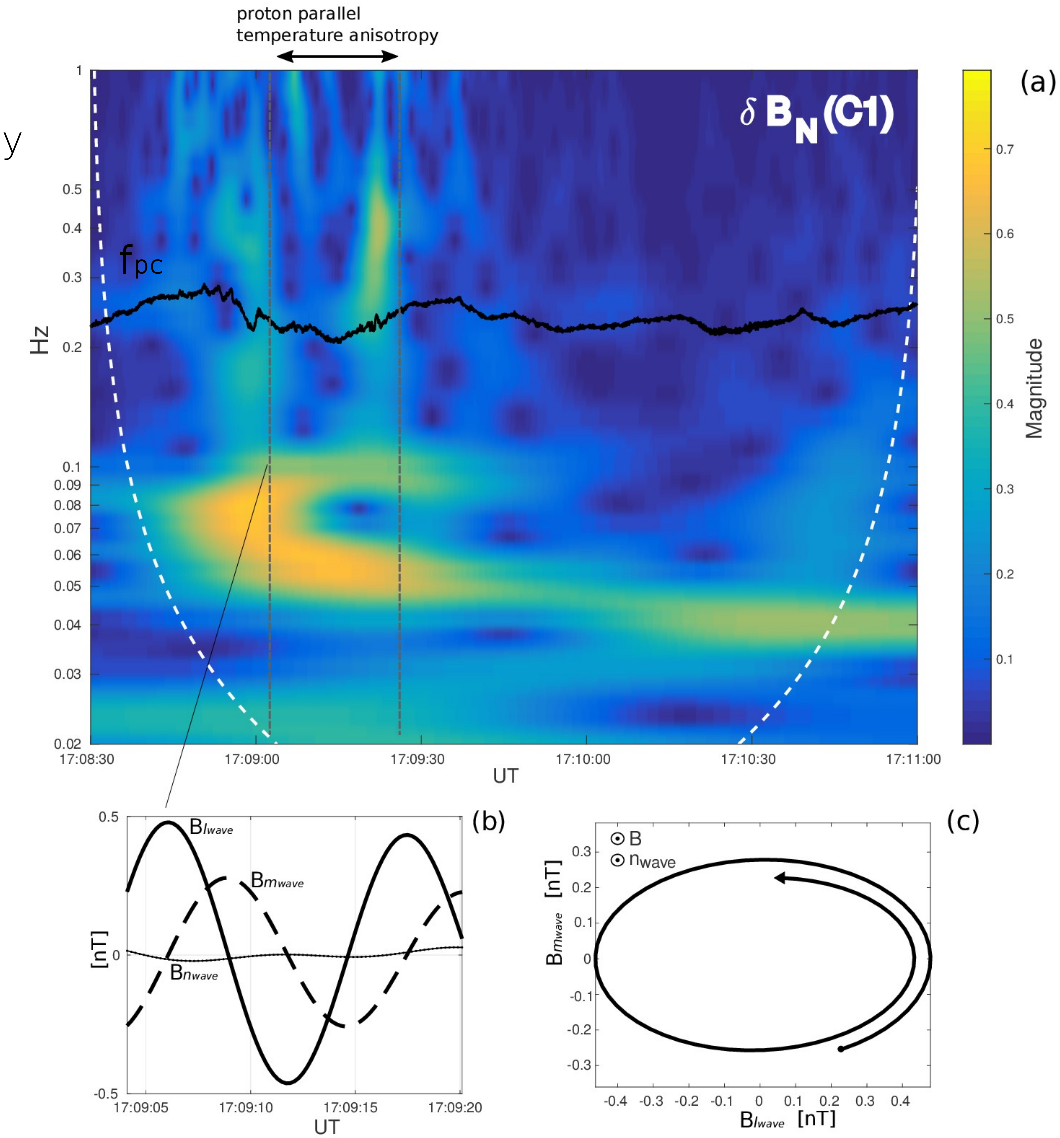
Counter-streaming ion beams

Waves associated with temperature anisotropy

We analyze fluctuations observed at the time

associated with the parallel temperature anisotropy
δt = 17:09:04-17:09:20
$f = 0.08 - 0.11$ Hz
⇓
Minimum variance analysis:
[Sonnerup and Cahill, 1967; Thorne, 1973, Smith and Tsurutani, 1976]
wave orientation in LMN is
l = (0.02, 0.64, 0.77)
m = (0.74, −0.53, 0.42)
N = (0.68, 0.56, 0.49)
Normal is well defined: λ med /λ min = 188
⇓
] wave is parallel to the background field
→ right-hand rotation,
propagation angle ~ 23°, ellipticity is = 0.57

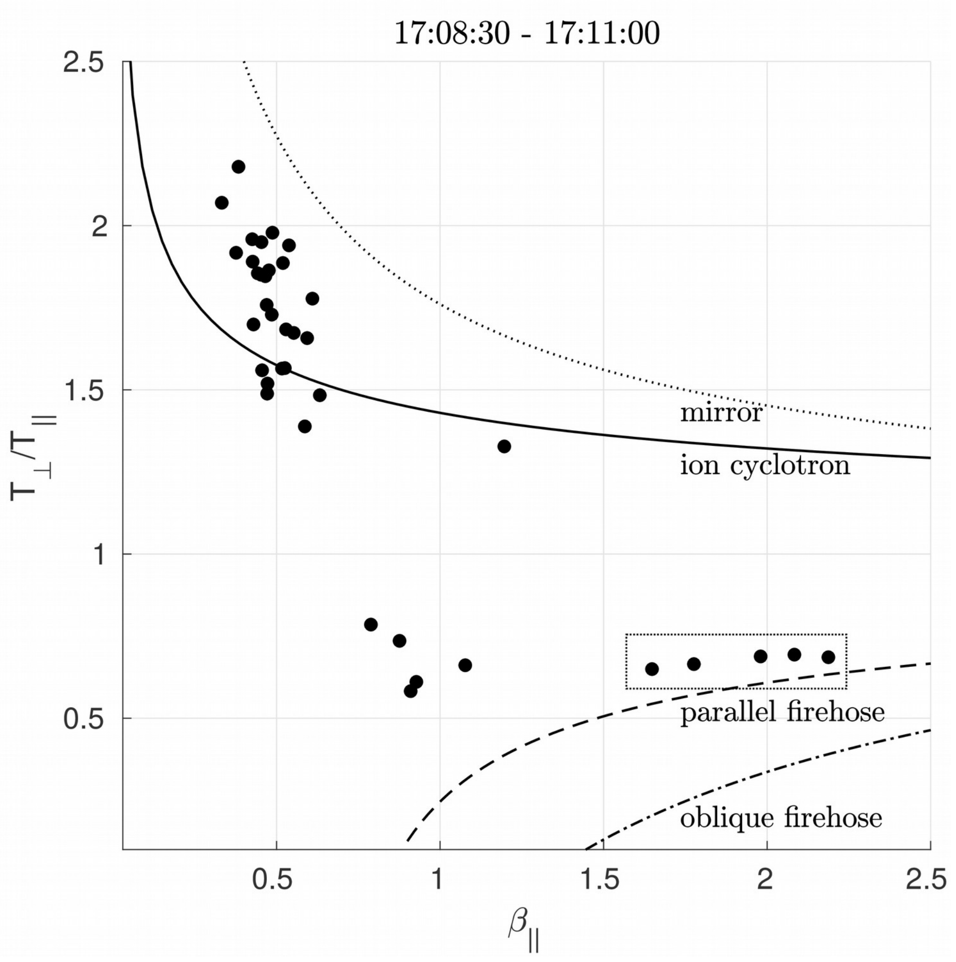
Possible Doppler shift
plasmoid is moving tailward ≈ −130 km/s
[Alexandrova et al. 2016]
ion bulk speed tailward ≈ 160 km/s
Alfvén speed is ≈ 800 km/s
→ the Doppler shift is roughly ≈ 0.09 Hz,
Real wave frequency is $f \approx 0.2$ Hz ≈ f_{pc}



one wave period observed ΔL ≈ 1950km ≈ 0.3 RE ≈ 3.4 di
the amplitude is $\delta|B|/|B_{bg}| \approx 0.03$

➡ Observed wave characteristics and frequency ranges are consistent with the low branch whistler waves, which are related to the linear firehose instability [Gary+1998]

Analysis of plasma stability I



Qualitative estimates for the plasma stability

comparison between $T_\perp/T_{||}$ and $\beta_{||}$

measured in between the two X-lines

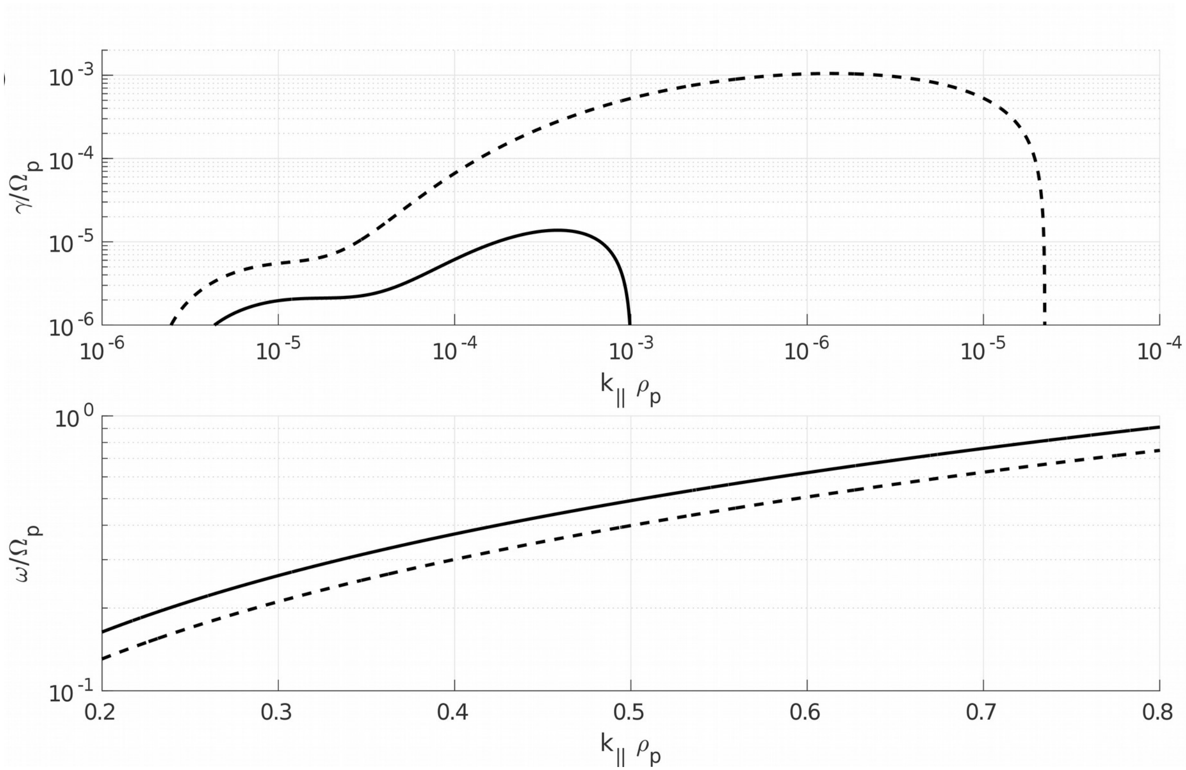
with the predictions of Vlasov linear theory
for the marginal stability thresholds of typical plasma
Instabilities calculated

for the maximum growth rate
$\gamma \approx 10^{-3}$,
according to [Hellinger+2006]

Points correspondent
to the parallel temperature anisotropy
and firehose-related waves

Analysis of plasma stability II

To investigate the growth rate of the possible firehose instability,
we solve the Vlasov-Maxwell equations by using WHAMP solver



Observed parameters
(solid line)

B ≈= 17nT
$T_e \approx 1$keV
$n = 0.16$cm^{-3}
$T_i \approx 5$keV − 5.6keV
$T_\perp/T_{||} \approx 0.5 - 0.67$

Temperature might be underestimated
→
Anisotropy and Ti increased by 10% and 30%, respectively
(dashed line)

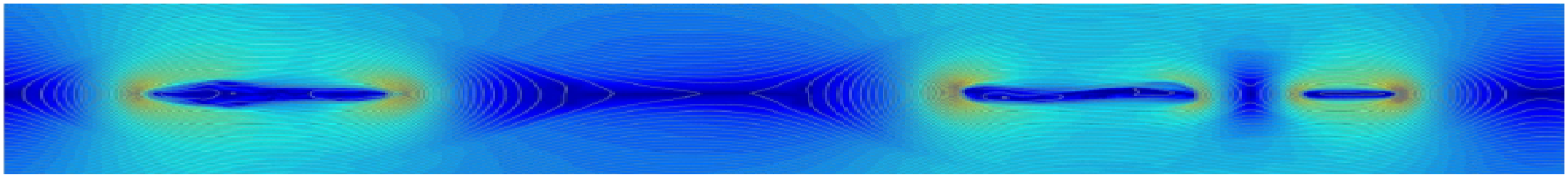
WHAMP solver [Rönnmark, 1982],
(realization of irfu-matlab IRF, Sweden)

Positive (but small) growth rate corresponding to the right-hand polarized waves f = 0.07 − 0.08Hz propagating parallel to magnetic field

→ consistent with the firehose instability and similar to the observed waves

Reconstruction of observations with PIC

iPIC3D implicit PIC code [Markidis+2010]
(A. Divin)



x axis is parallel to reconnecting field (~ L), y axis is normal to the current sheet (~ N)

2D rectangular domain with dimensions (Lx , Ly), model is translationally invariant in z

Initially two conventional Harris current layer

box dimensions (Lx , Ly) = (60di , 15di)
number of grid points in each dimension (Nx , Ny) = (2304, 576)

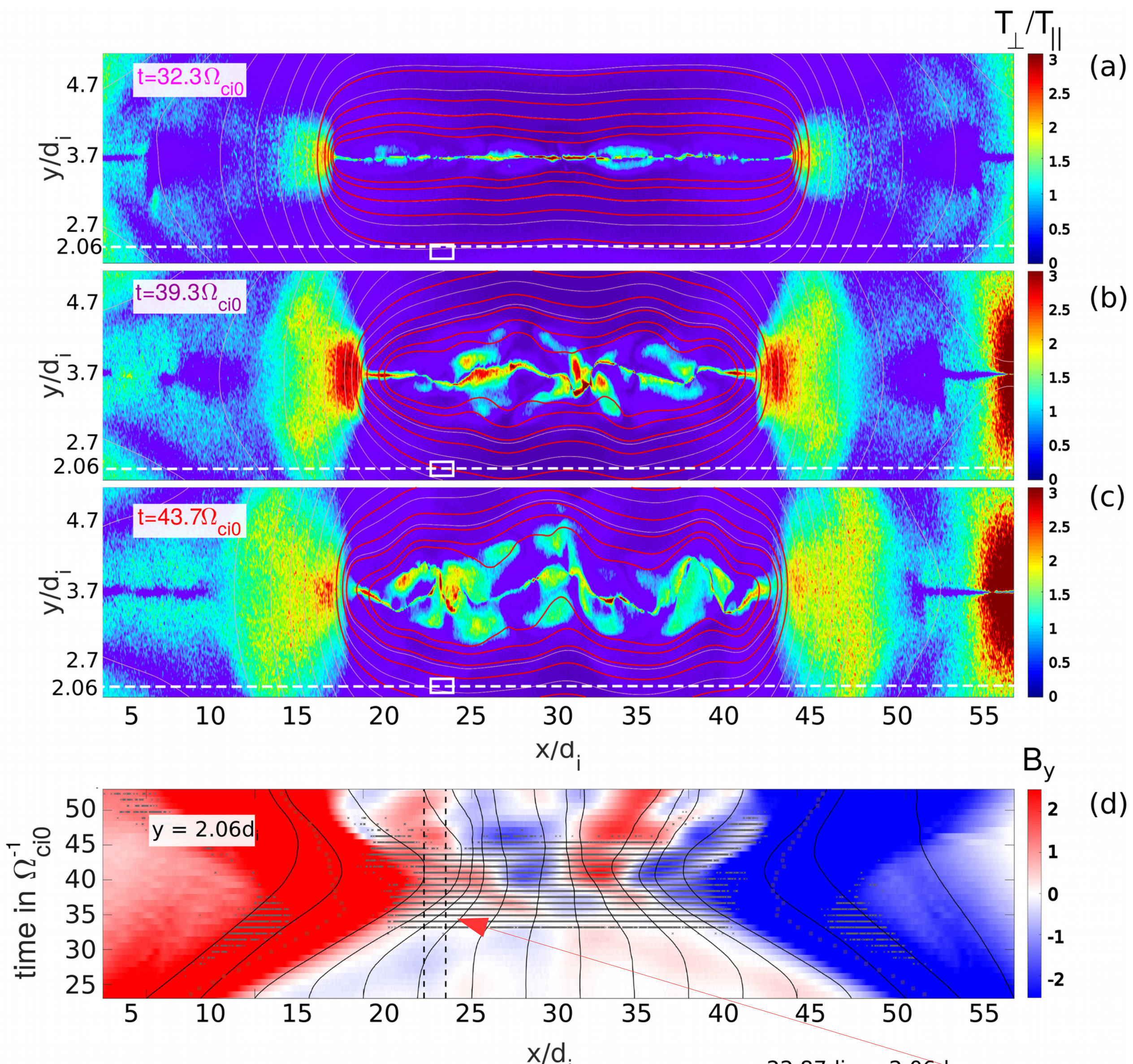
$m_i/m_e = 256$, $c/V_A = 276$

Magnetotail-like normalization $n_b = 0.1 n_0$ Ti /Te = 5
length unit (di ≈ 509 km) computed from plasmoid edge density 0.2 cm^{-3}
Alfvén speed of 780 km/s
the ion cyclotron frequency $\Omega_{ci0} \sim 1.5\ s^{-1}$

localized X-point perturbation ignites reconnection at (0, Ly /4)

To mimic the dynamical stage of the plasmoid evolution, we impose periodic boundary conditions and allow plasma jets to run head-to-head producing the domain-large plasmoid

Reconstruction of observations with PIC



Plasmoid formation
and compression

(T⊥ /T|| > 1) in the plasmoid core
and reconnection fronts

(T⊥ /T|| < 1) at the edge

Plasmoid shrinks

at the edges
strong bending
of magnetic field lines

inside the plasmoid
Magnetic field becomes
strongly inhomogeneous

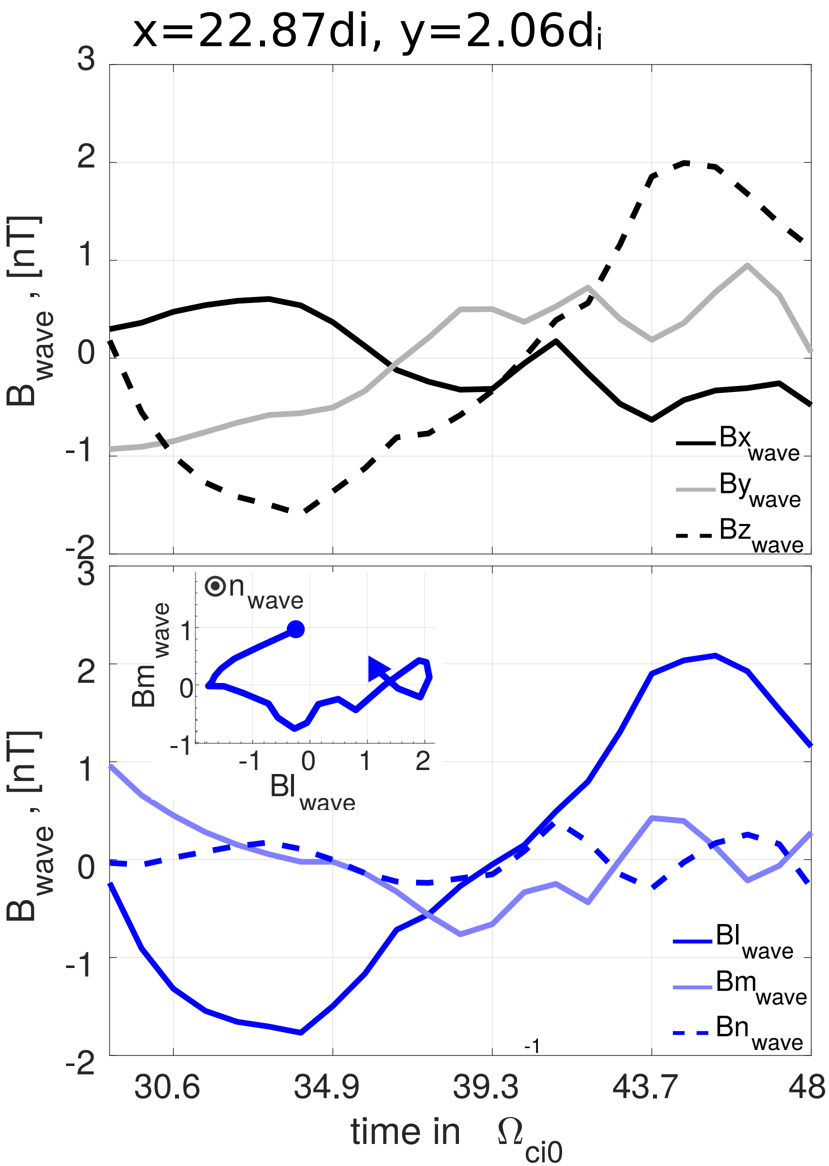
At the edge of plasmoid
At the time of strong interaction
between the counter-streaming jets:

Plasma overcomes the firehose
marginal stability threshold

Magnetic field fluctuations grow

temporal evolution of the normal to the current sheet
magnetic field (red and blue) and the regions where
temperature anisotropy overcomes the marginal stability
threshold of the firehose instability (gray crosses)
for a cut in y = 2.06di

Wave analysis in PIC



In the middle of the selected region (a white rectangle marked at the plasmoid edge on previous slide)

the magnetic field temporal changes represent one wave period

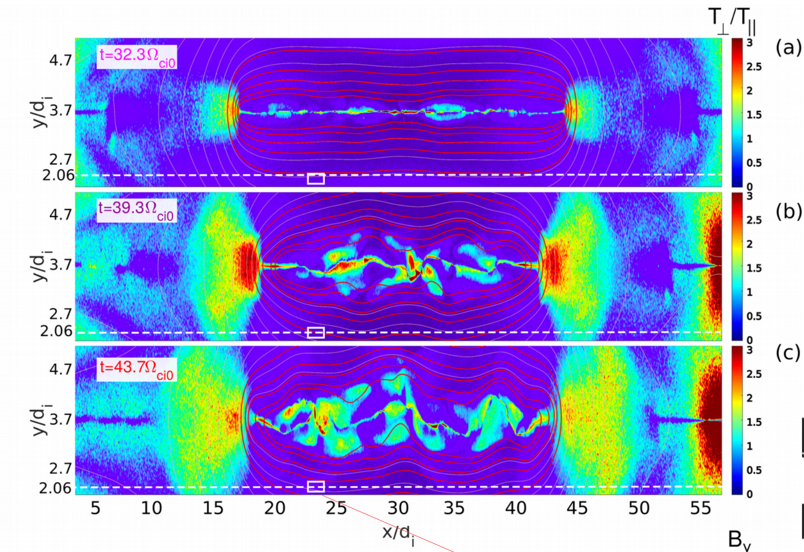
the MVA analysis gives the orientation of wave normal
Nwave = (0.92, 0.11, 0.3),
Lwave = (−0.25, 0.9, 0.34),
Mwave = (0.28, 0.41, −0.87),
in PIC (x, y, z) coordinates.

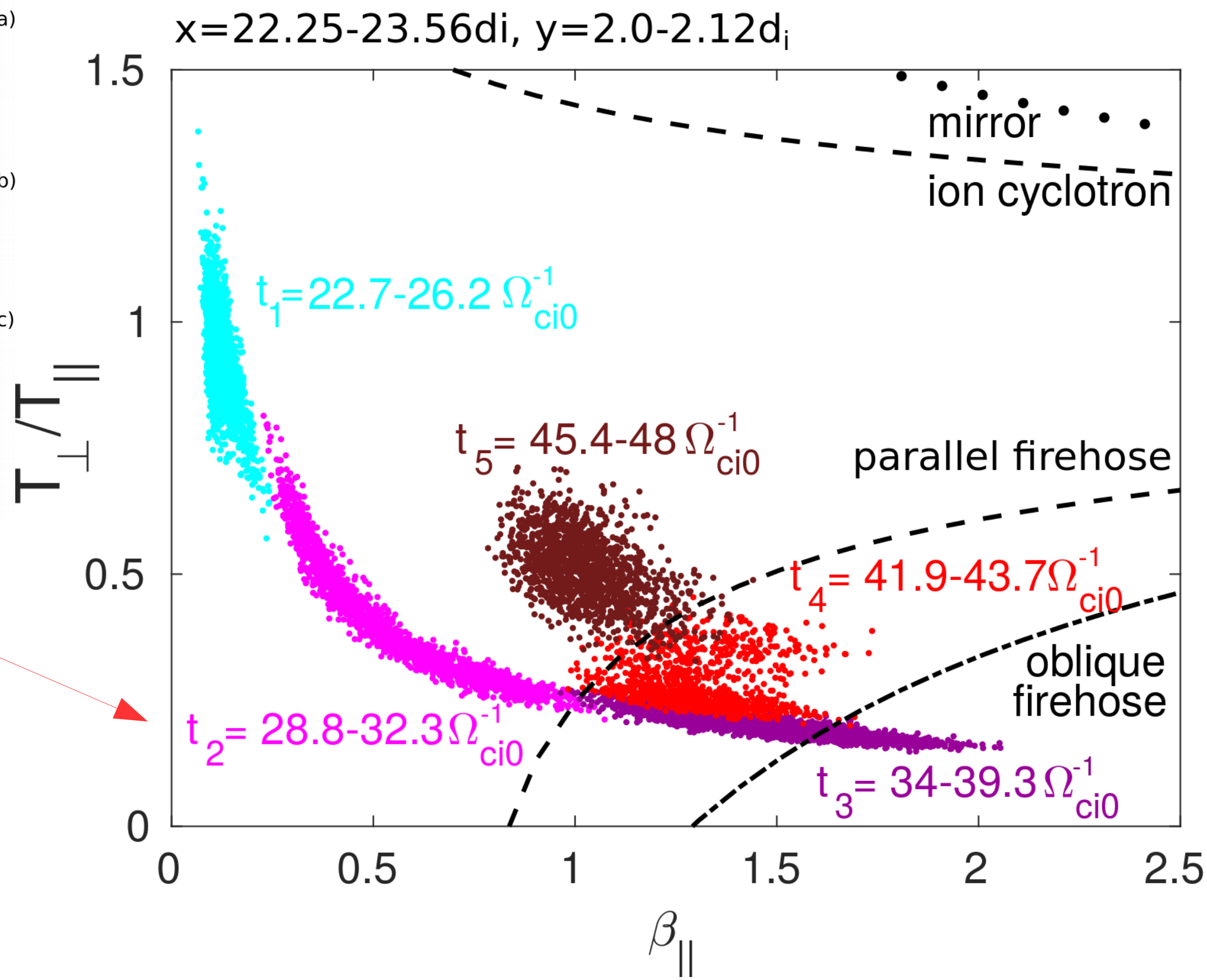
rotation of magnetic field in the plane perpendicular to the normal direction, Indicate right-hand elliptical polarization.

Fluctuations show characteristics typical for the firehose instability, with the magnitude of about $\delta|B|/B \approx 0.15$

the amplitude of the magnetic field fluctuations changes in time revealing the nonlinear evolution

Analysis of plasma stability in PIC





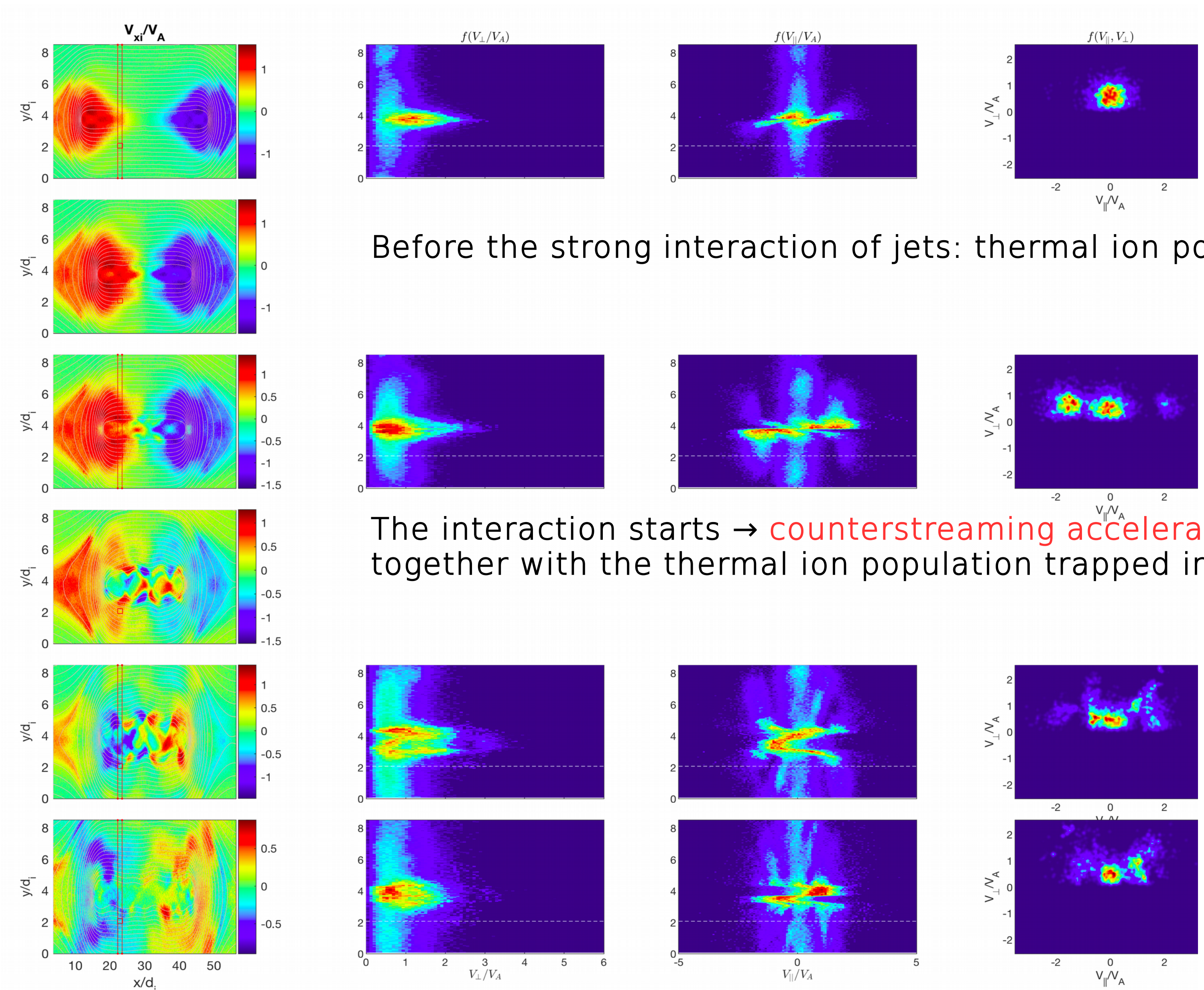
Plasma
in the selected region
at the edge of the plasmoid

In course of time is

isotropic and stable →
more anisotropic →
largerly overcomes the firehose threshold →
Becomes more isotropic and close to the marginal stability →
stable

Temporal evolution of plasma stability at the edge of the plasmoid
Is consistent with the development of the firehose instability

PIC ion distribution at the edge of the plasmoid



Before the strong interaction of jets: thermal ion population

The interaction starts → counterstreaming accelerated ion beams, together with the thermal ion population trapped inside plasmoid

As a result of jets interaction: particle beams are scattered more to perpendicular direction, indicating the interaction with the firehose waves

Conclusions

According to the in situ observations of multiple reconneciton in the Earth's magnetotail and their reconstruction by PIC simulations:

Ion firehose instability develops at the periphery of the plasmoid
between the reconnection X-lines
leading to deceleration of ions accelerated by reconnection

➡ may reduce the efficiency of reconnection

more details in [arXiv:2004.08280]