MMS observations of reconnection separatrix region in the magnetotail at different distances from the active neutral X-line

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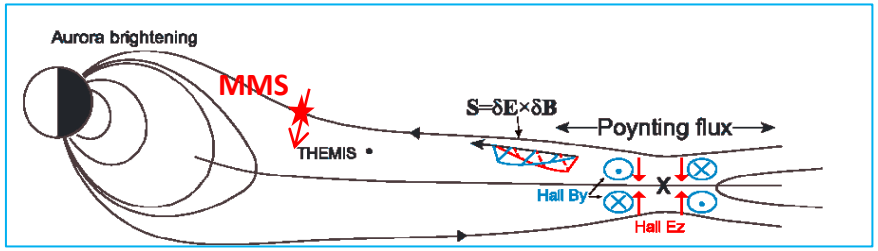

Goals of this study:

- ✓ Investigate meso-scale spatial structure of magnetotail Separatrix Region (SR) using MMS observations during active reconnection events
- ✓ Analyze the distance dependence of SR spatial structure and appearance of Hall-type E&B perturbations
- ✓ Evaluate distance to the XNL based on energy-dispersion of hot Earthward p-beam *taking into account the convection and SR boundary motion*

Event selection criteria →10 events in 2017-2018

- ✓ Burst mode
- ✓ Quick crossings of separatrix region SR on Earthward side of XNL (Earthward p-beam)
- ✓ Indications of active reconnection: hot e&p beams, polar rain gap, *in addition* -convection across boundary (timing *vs* convection)
- ✓ Clear energy dispersion of hot proton beam

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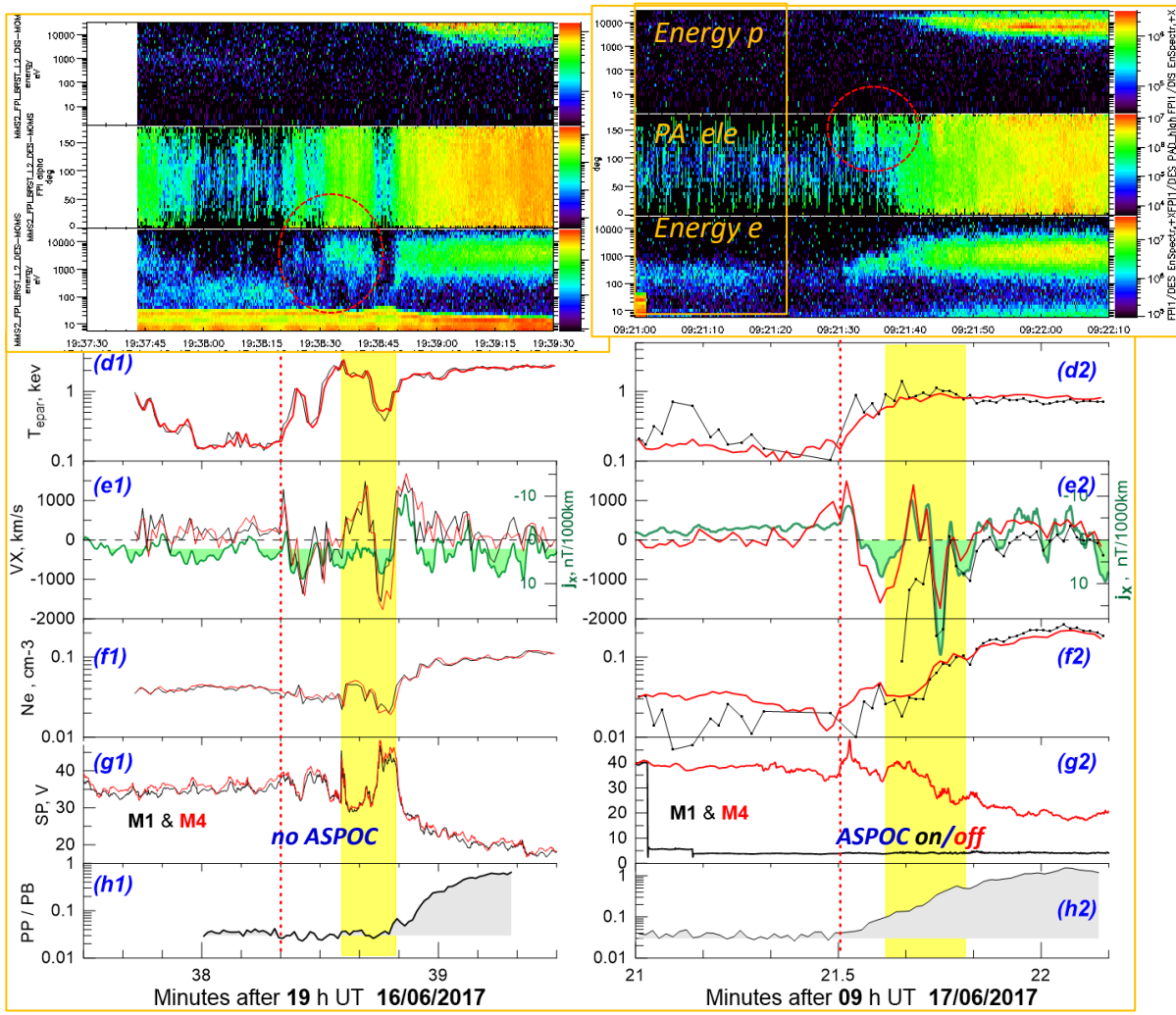
Active PSBL observations close to the XNL (1)

Crossings near the X-line identified by observing '*Hall-type*' electrons

- hot proton energy-dispersed beam
- accelerated e-beam toward the XNL
- accelerated e-beam &polar rain gap
- Te increase at separatrix
- **earthward FAC pulses** carried by tailward pulses of net electron flux Vex
- Low e-density (&cavities) before arrival of hot proton beam
- spacecraft potential variations (without ASPOC) consistent with Ne (also in low-density region, incl.cavities)
- plasma beta

Tailward hot e-beam at separatrix

Event #1 *Event#2*



*We look at **meso-scale structure** as seen at 1sec resolution of E,B and plasma parameters*

Hall-type Ez (and By) intervals (see next slide)

Active PSBL observations close to the XNL (2)

- hot proton energy-dispersed beam + cold ions (CI) convecting at E/B velocity, yellow arrow indicates the CI heating time

- 1/V analyses of energy dispersion and inferred distance to acceleration site (XNL)

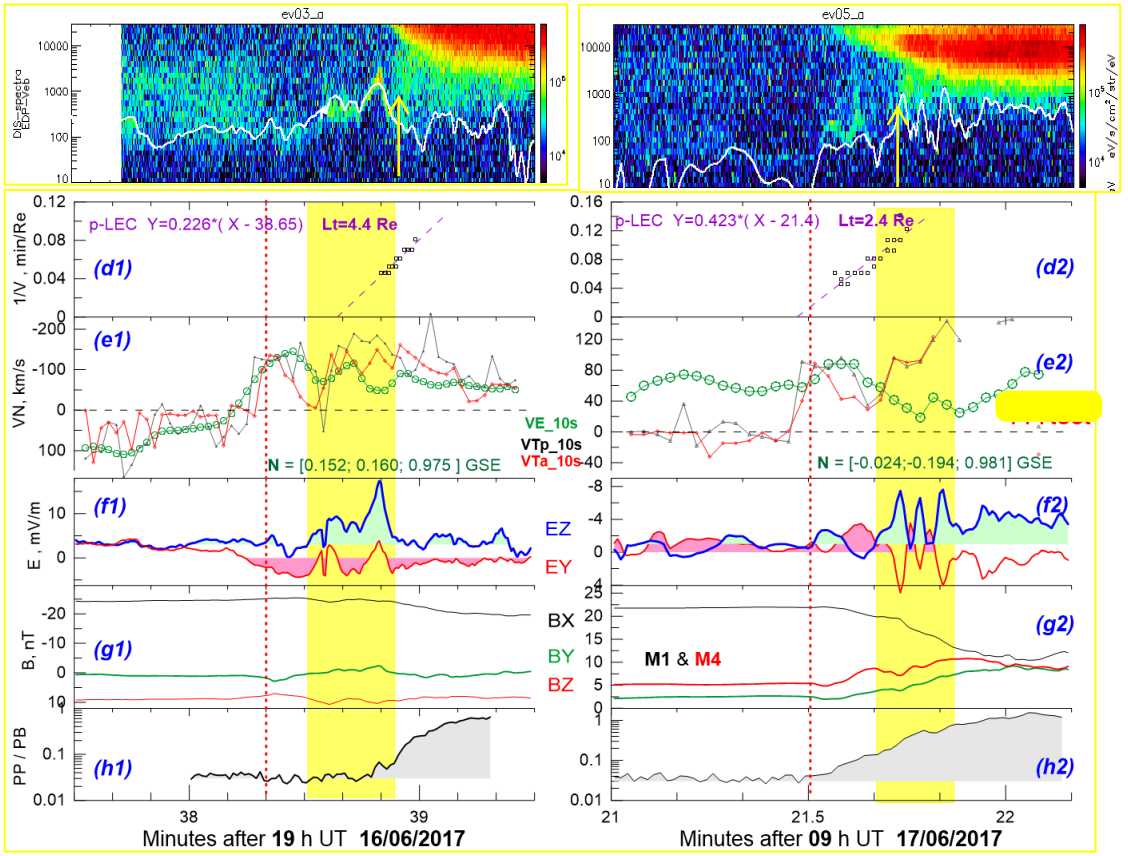
- velocities along normal to the current sheet: convection velocity **VE** and timing velocities **VT** (from 2 methods) which may indicate the separatrix velocity. VT is comparable to VE. The cases VT>VE may indicate the reconnection

- E-field: strong positive (negative) Hall-type EZ in southern (northern) PSBL in events #1 (#2)

- magnetic field

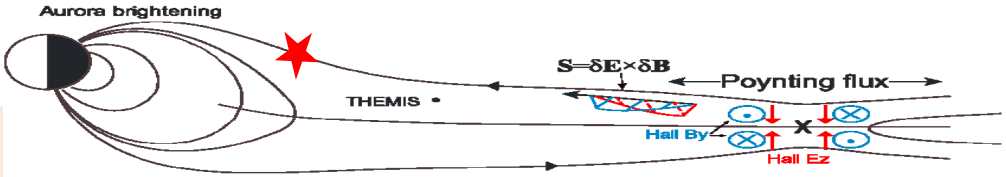
- plasma beta

Event #1 *Event#2*



Hall-type Ez (and By) intervals (HAR)

Active PSBL observations <u>far from XNL</u>



Event #3

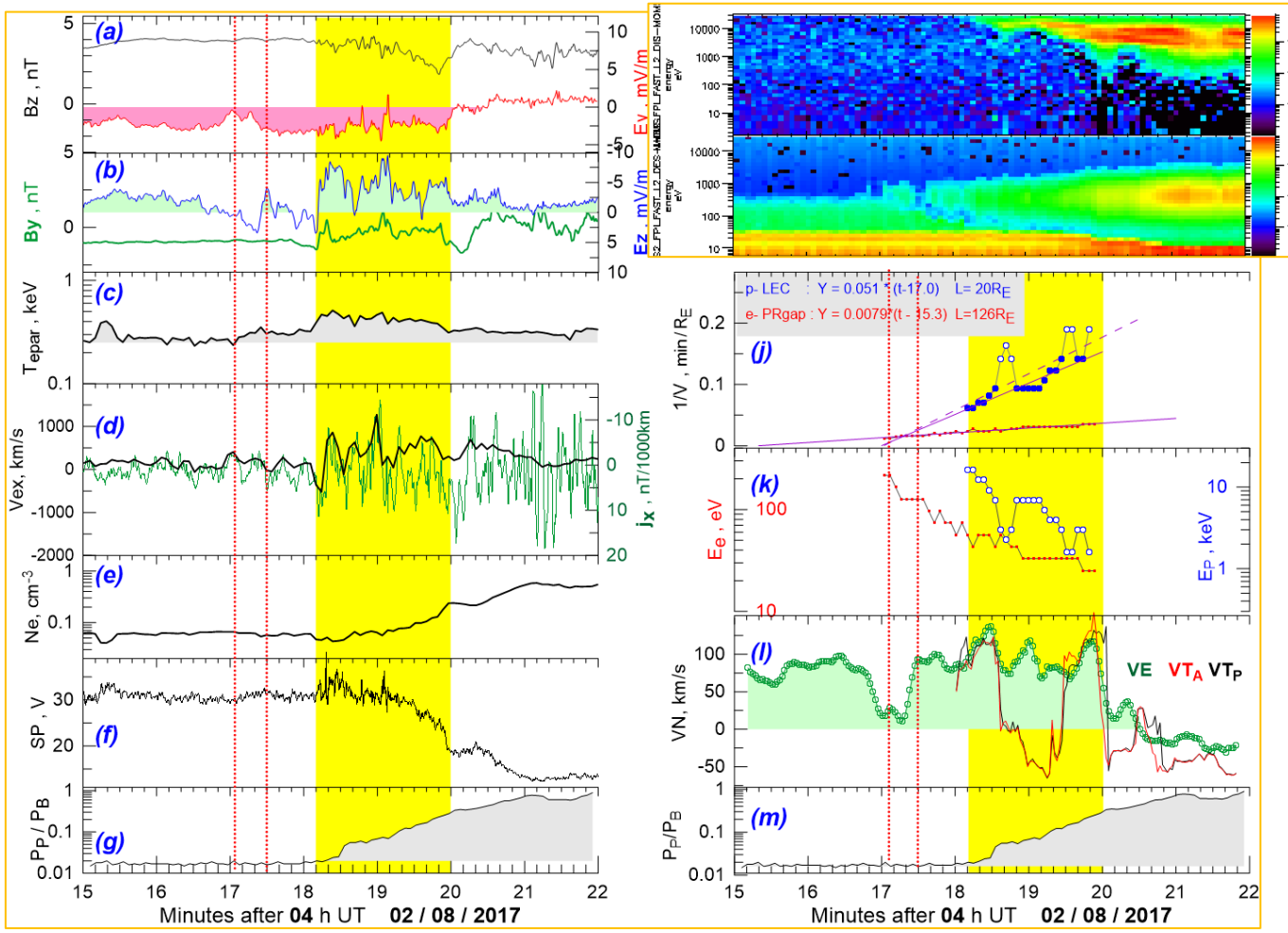
- first half of energy-dispersed hot p-beam roughly corresponds to the interval of intense Hall-type E&B perturbations (*panel b*) in the low density region (*panels e, f*)

- 1/V analyses of p–and e-dispersion indicate <u>distance to XNL of 20-100Re</u> *(panel j)*
- low energy of accelerated electrons is consistent with <u>distant tail origin</u> *(c)*

- intense **FAC**s in the HAR nicely correlate with **Vex** *(panel d)*, only first Vex pulse was in tailward direction (also associated with Ne drop)

- persistent northward plasma convection till 04:20. **VT** twicely approaches **VE** , interval of opposite direction is hard to interprete in terms of separatrix motion and reconnection

<u>This case nicely demonstrate Hall-type E&B and similar PSBL structure observed very far from reconnection source.</u>



Hall-type -Ez and +By interval (panel b)

Active PSBL observations far from XNL

Event #4

•Non-monotonous appearance of p-beam due to N-S PSBL motions *(pan.j)*

• very intense Hall-type E&B perturbations (*panel b*) in the low density region (*e*) associated with brief appearance of p-beam; full development of energy-dispersed hot p-beam delayed by 2min

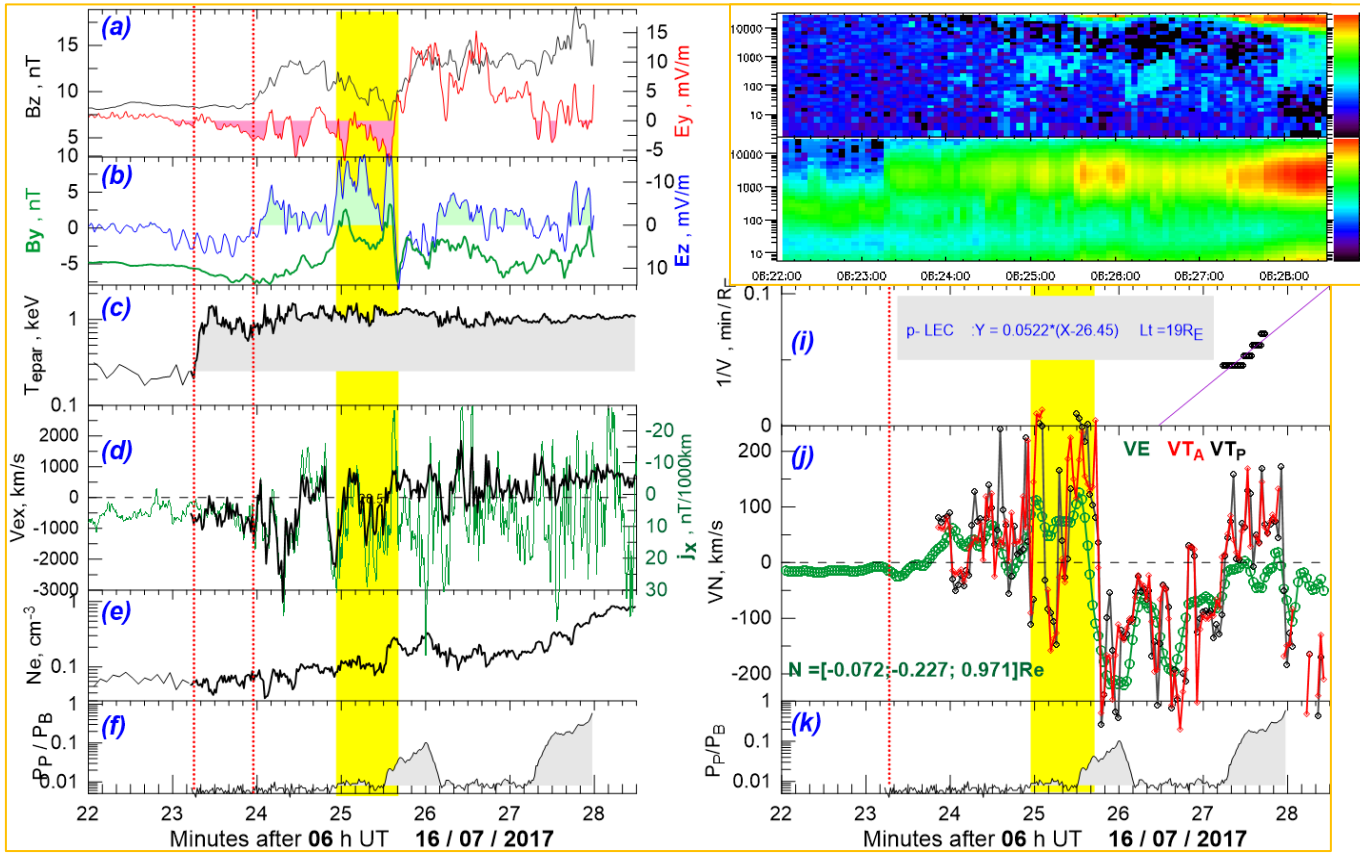
• high energy of accelerated electrons*(c)*

• 1/V analyses of p–dispersion indicate distance to XNL of ~19Re *(panel i)*

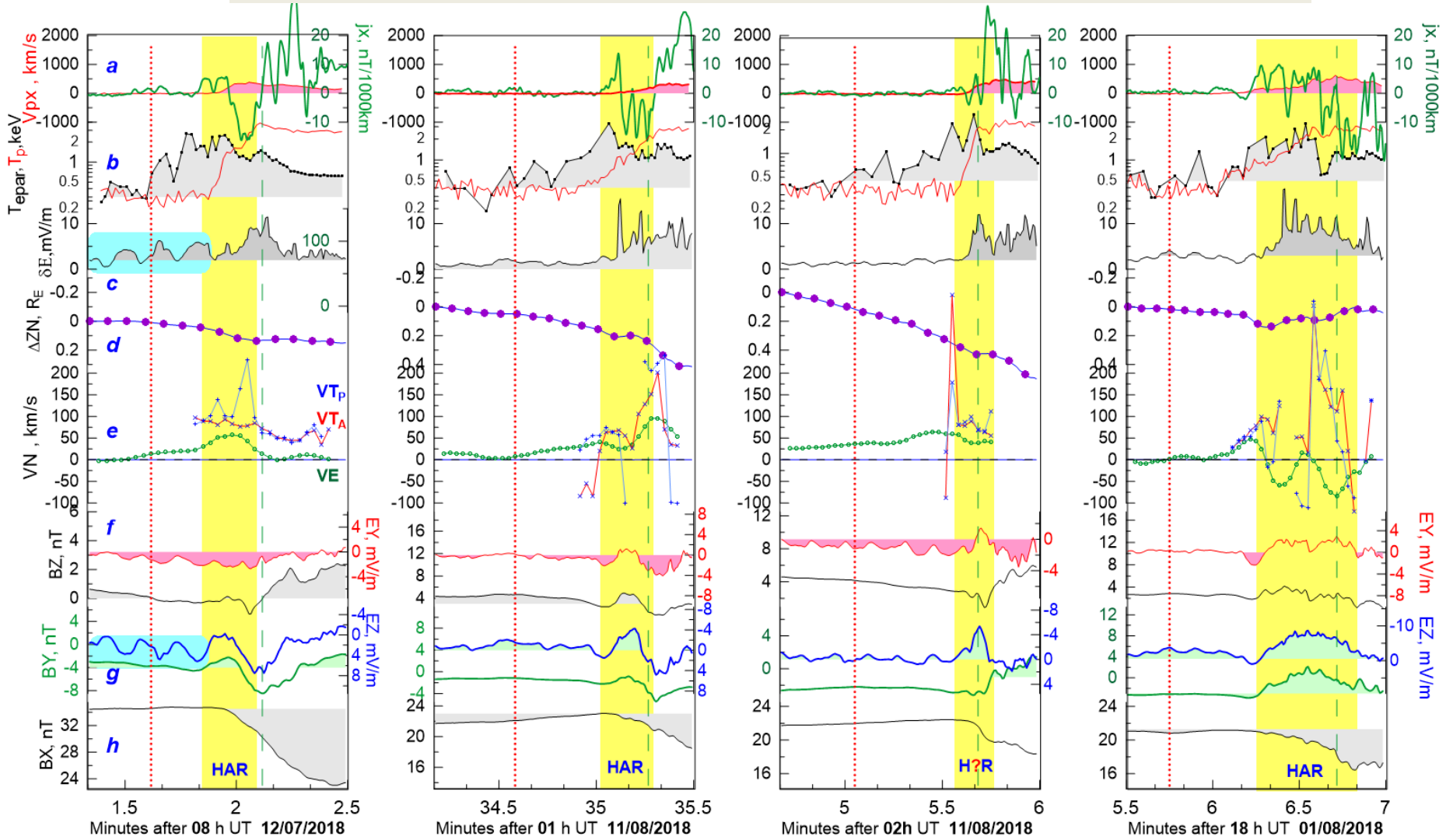
• intense FACs in the HAR and around nicely correlate with **Vex** *(d)*, two intense tailward **Vex** pulses observed prior to HAR registration.

• intense northward-then southward plasma convection, **VT** is variable but generally follows **VE**, during p-beam dispersion **VT>VE** indicating reconnection

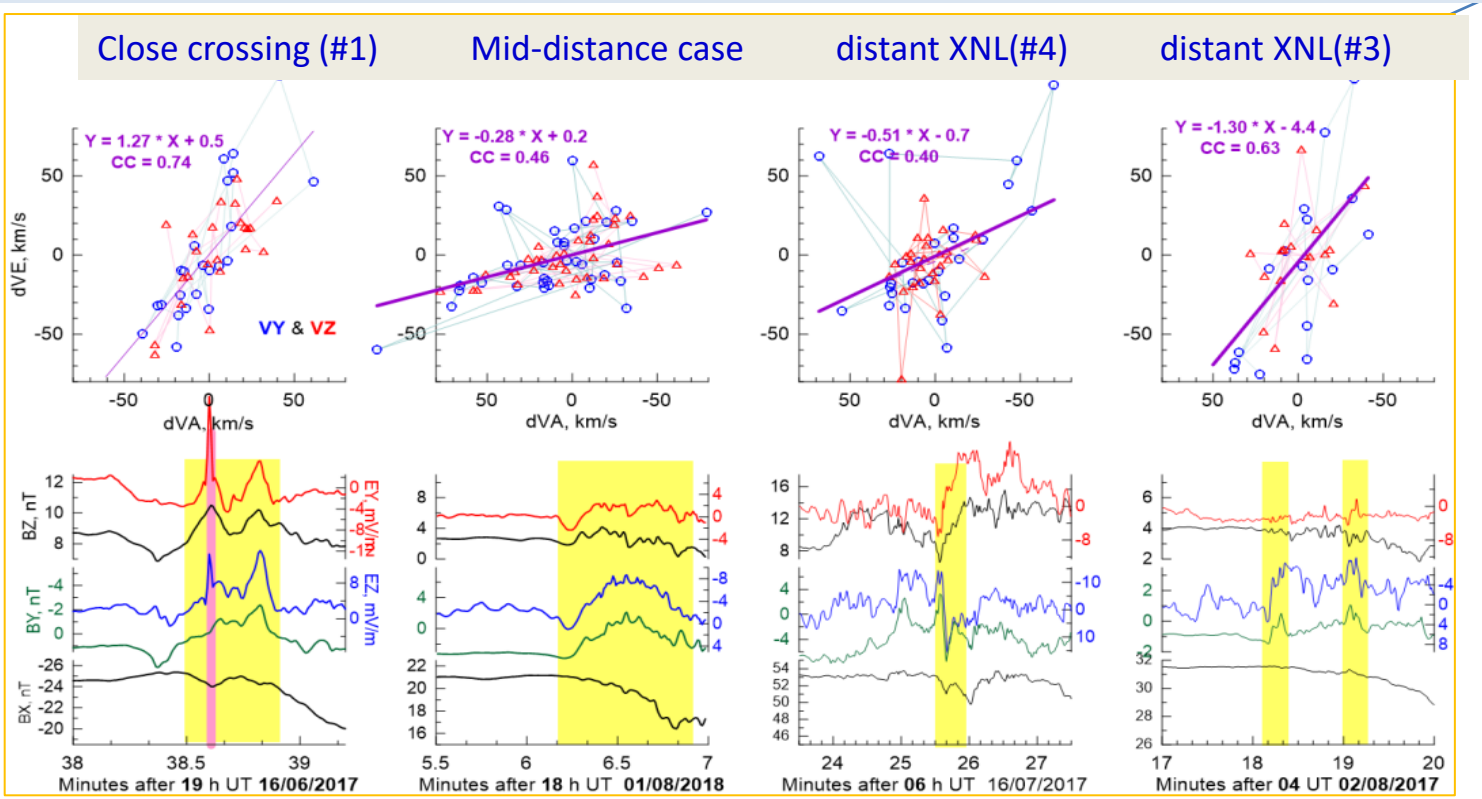
This case demonstrates Hall-type E&B and similar PSBL structure observed far from reconnection source (≥19Re)



Separatrix region crossings in four mid-distance (~10R_E) events



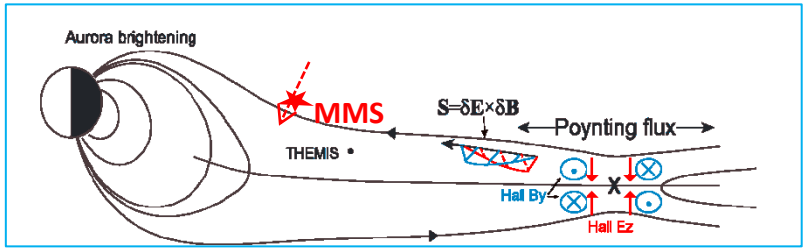
Alfven wave test of δE & δ B in the Hall-type region



We only analyze those short time intervals which visually manifest the correlation between pairs –Ez,By and Ey,Bz (they are marked by yellow strips). For them, in the upper row, we compare the 1sec increments of observed y- and z-components of convection velocities $dVE_i = [dExB]_i/B^2$ with their Alfvenic prediction $dVA_i = (dB_i/(\mu_0\rho)^{1/2}$.

- the regression slopes ($\delta E/(\delta B\ V_A)$ ratio) are not far from 1, consistent with AW related origin
- it can be as high as 1.3 (#1 and #3) and as low as 0.3 (mid-distance case)
- *AW –like intervals neighbour to the intervals of intense Hall-type EZ of different origin (?)*

Summary



During 10 MMS inward crossings of active separatrix region, occurred in a wide range of distances from XNL *(from a few R_E to several tens R_E), we typically observe:* the thin layer of low density plasma consisting of lobe-like cold ions and hot electron beams (**eSR**), which is followed by the region containing significant Hall-type E&B perturbations (**HAR**) and also by energy-dispersed hot proton beam region (**pSR**), last 2 regions usually significantly overlap in space, except for 2nd distant crossing.

This **general structure** is consistent with theoretical/simulation picture of reconnection structure (e.g. Gonzalez and Parker ed., Magnetic Reconnection, Springer 2016, Lapenta et al.2016, etc)

- **Electron separatrix region (eSR)** has low lobe-like density, may contain density cavities (associated with tailward e-beams)
- At middle and large distances the portion of electron separatrix region (between separatrix and HAR) is often void of accelerated tailward e-beam and associated earthward FAC.
- Pulse of net tailward e-flow carrying earthward Hall FAC can still be observed at far distances, mostly in the outer portion of HAR region.

- **Intense Hall-type EZ** field may or may not be associated with observable +By perturbations. Correlated E & B Hall-type perturbations are consistent with Alfven Wave-related transport from the reconnection source, the Alfvenic ratio $\delta E/(V_A \delta B)$ was estimated between 0.3 and 1.3 in studied examples , unlike the expectations of kinetic AW mechanism.
- **HA region** is associated with profound plasma property changes, including the e-density growth from lobe-like values, heating of cold ions (usually in the innermost HAR part), it is filled by intense structured field-aligned currents and hosts the intense E-field fluctuations including Intense E spikes (e-holes) and LH waves.

- Long residence time (minutes) in eSR and HAR region and large perp. scales (~RE) are possible in cases of distant XNL events