Localized strong energy conversion regions and their use for identifying reconnection sites

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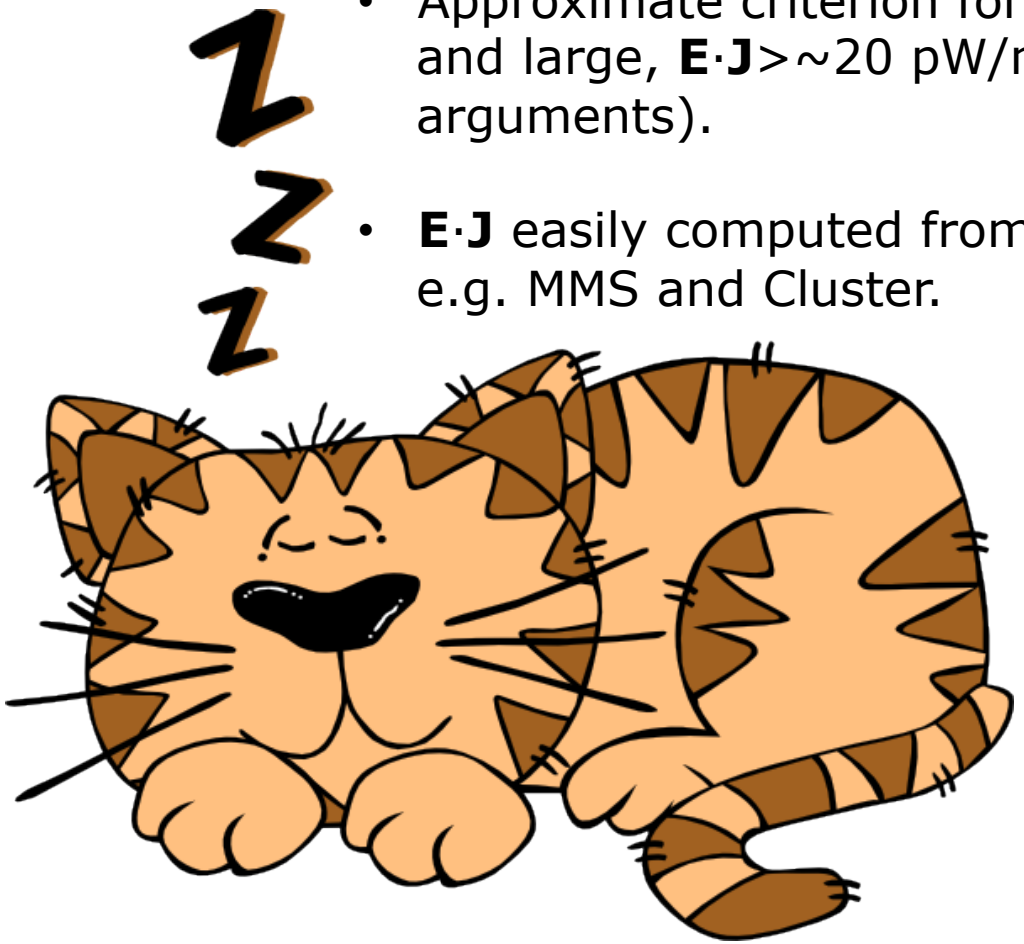
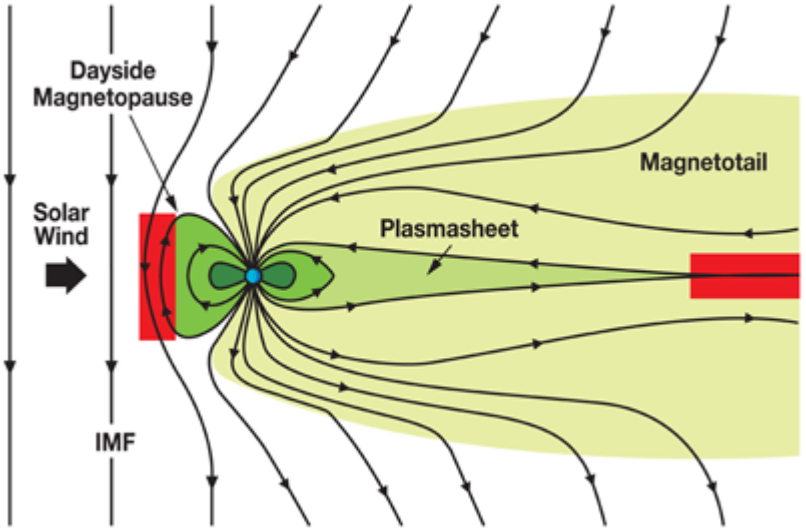
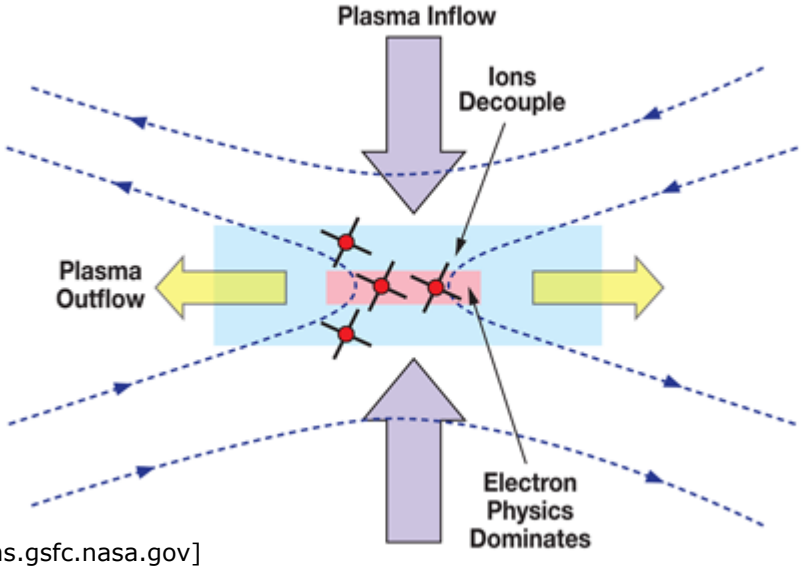
Key points

- Use of power density **E·J** as a method (primary indicator) for identifying potential reconnection events from large amounts of measured spacecraft data.
- Approximate criterion for tail reconnection: **E·J** positive and large, **E·J**>~20 pW/m^3 (consistent with theoretical arguments).
- **E·J** easily computed from multi-spacecraft data, e.g. MMS and Cluster.



Introduction: Reconnection





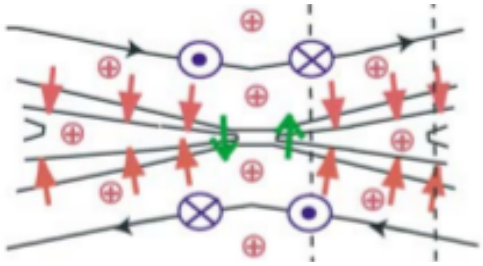
[http://mms.gsfc.nasa.gov]

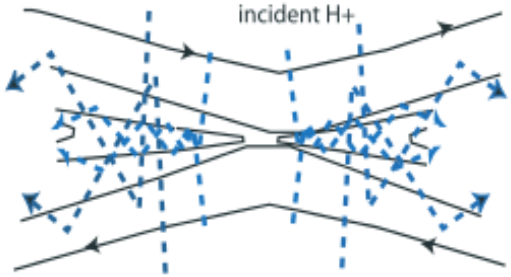
- Reconnection is a fundamental process.
- Change in magnetic topology. Magnetic → kinetic energy.
- Goal for MMS, Magnetospheric Multiscale Mission: Understanding reconnection.
- How to identify potential events from large sets of data?
  - Look for jet reversals, Hall E and B fields, …
  - Look for signatures of plasma acceleration!

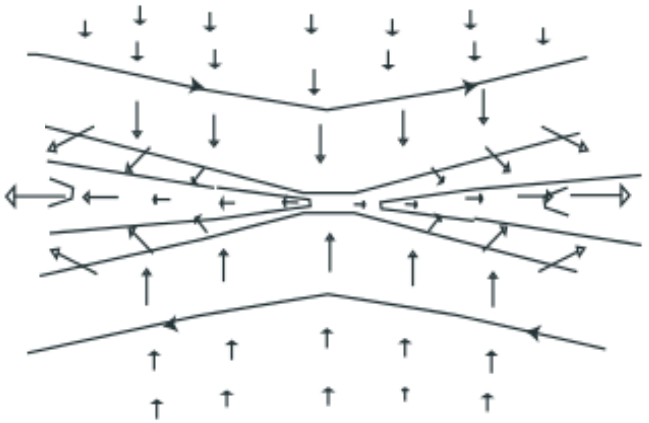
Reconnection load

- Physical process: Plasma energization at reconnection.
- Right: Acceleration of ions in ion/fluid picture.
- Strong localized energy conversion regions can be probed with **E**·**J**.
- Reconnection region should manifest itself as a load **E**·**J**>0 (accelerated jets).

Typical tail reconnection picture:

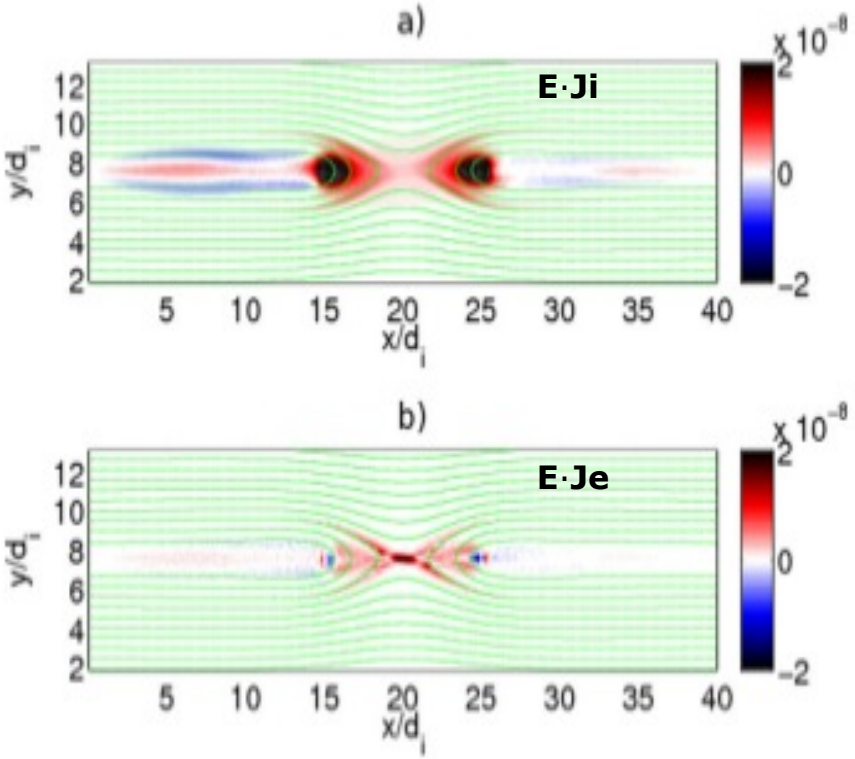






[Wygant et al., JGR 2005]

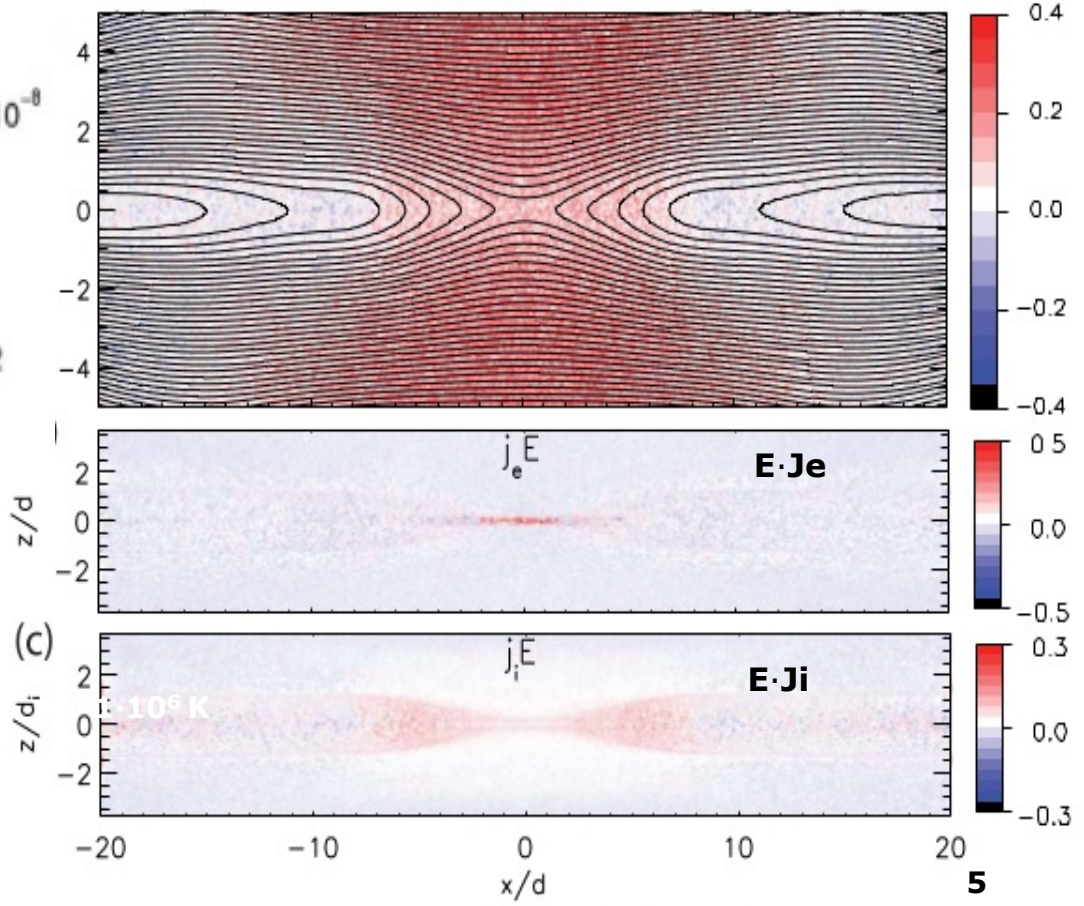
Reconnection load in simulations



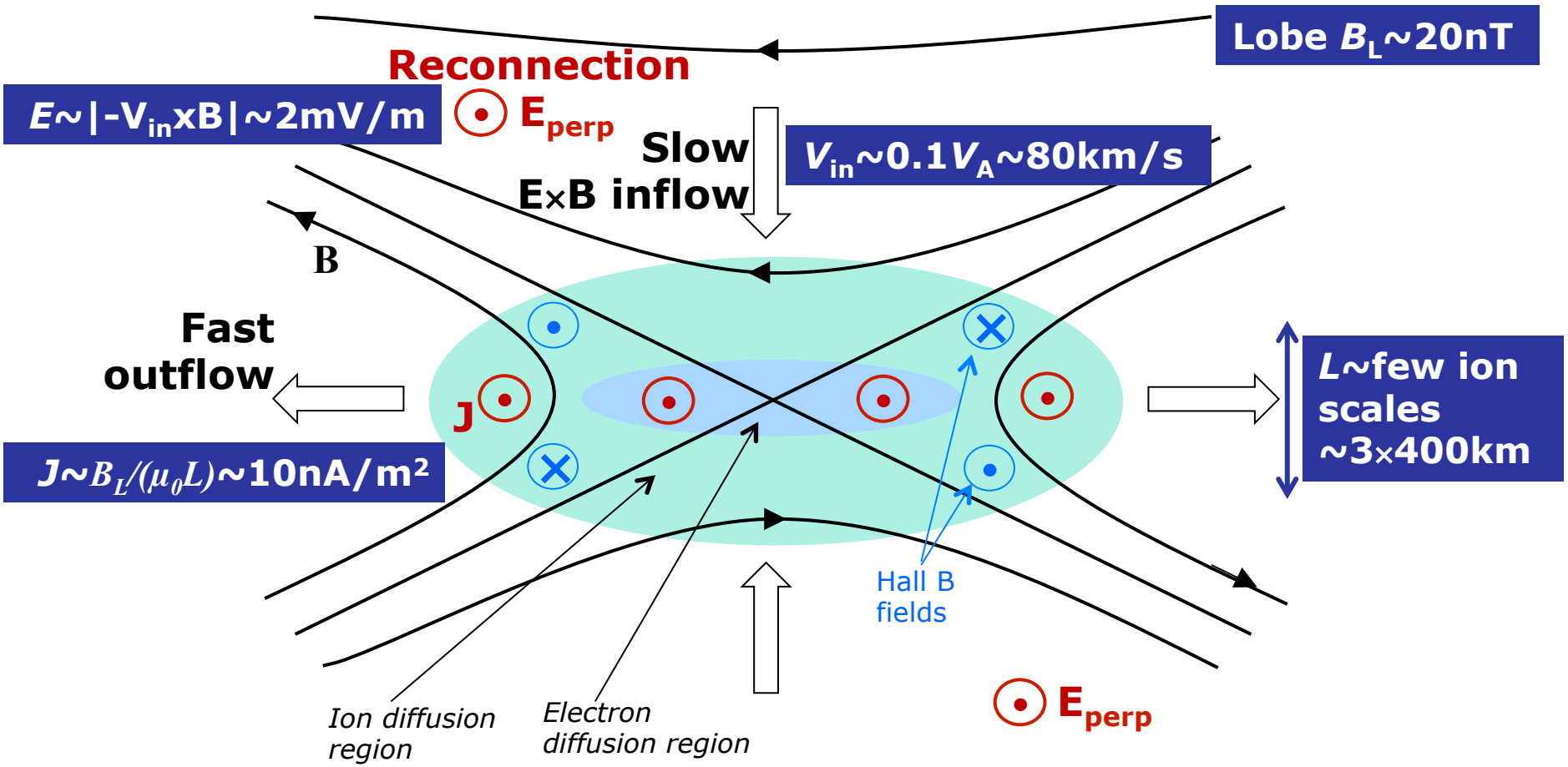
3D particle simulation PIC. *[Lapenta et al., Phys. Plasmas, 2014]*

- Ion and electron **E·J** in numerical simulations from cross-tail **E** and **J**.
- Width **E·Ji** ~ a few ion scales.
- (Electron region smaller.)

2D particle simulation PIC. *[Sitnov & Svisdak, JGR 2011]*



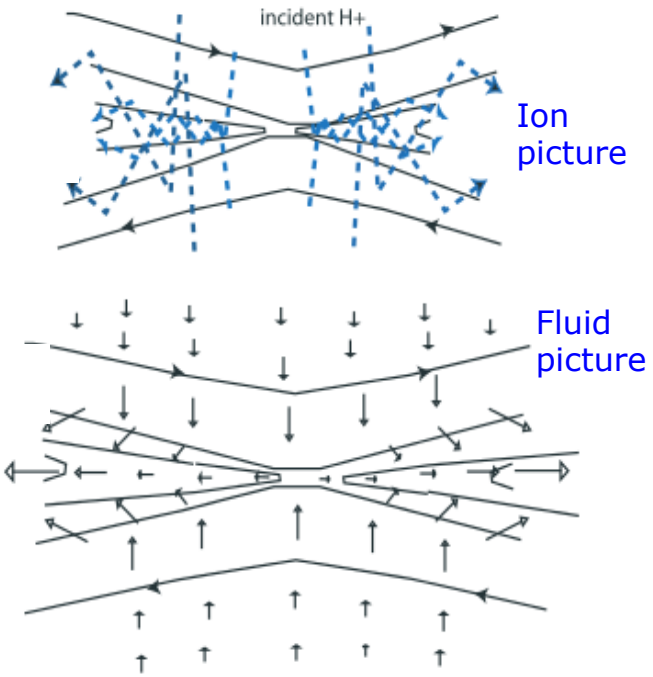
Tail reconnection load (typical energy change)

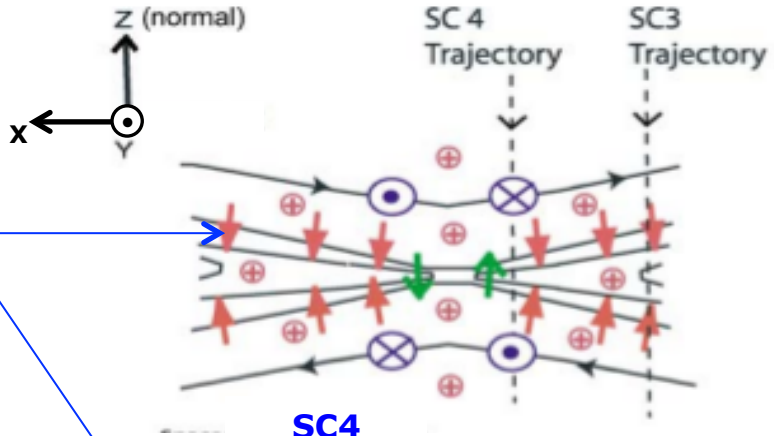


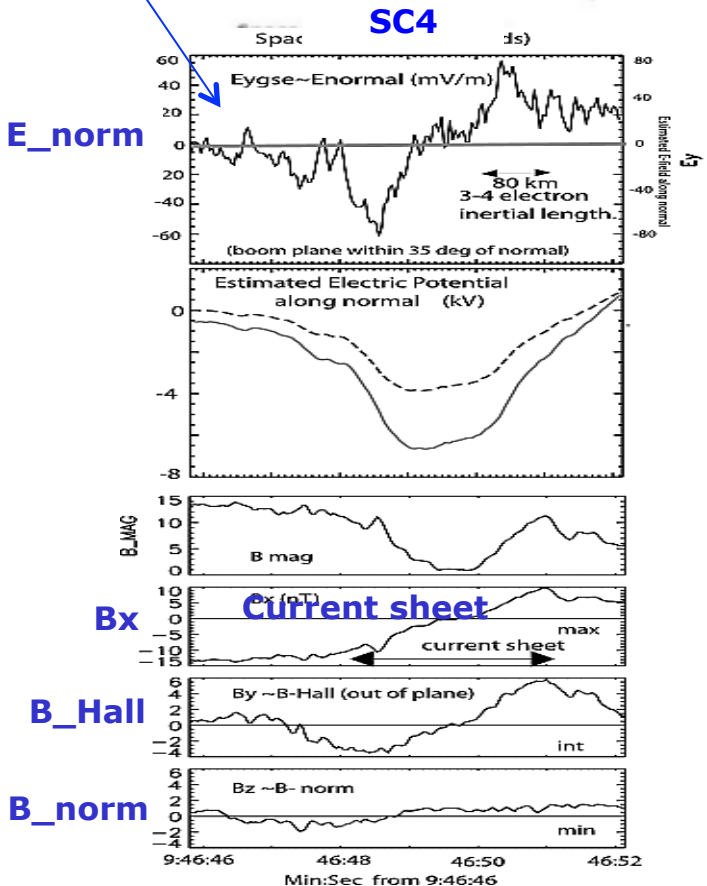
- Reconnection load (ion scales): E·J~(10nA/m²)·(2mV/m)~20pW/m³
- This is larger than typical values in plasma sheet [Hamrin et al., JGR 2011]

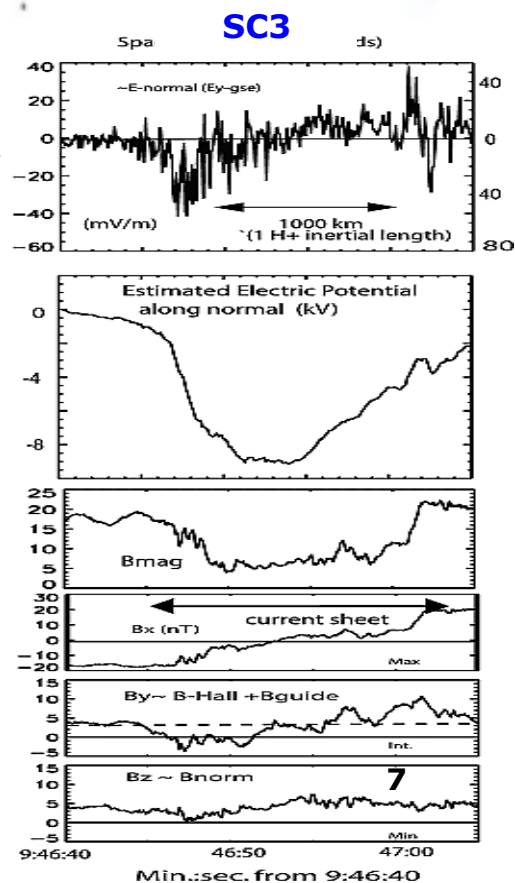
Example: October 1, 2001

- Cluster observations, ~22.4 MLT. Several Cluster crossings due to tail flappings. [Wygant+, JGR 2005]
- Intense $\mathbf{E_{norm}}$ (±60mV/m) observed in the ion decoupling region. 4-6 kV potential drop
- Ballistic acceleration of ions.
- Evidence for accelerated ion beams by $\mathbf{E_{norm}}$.









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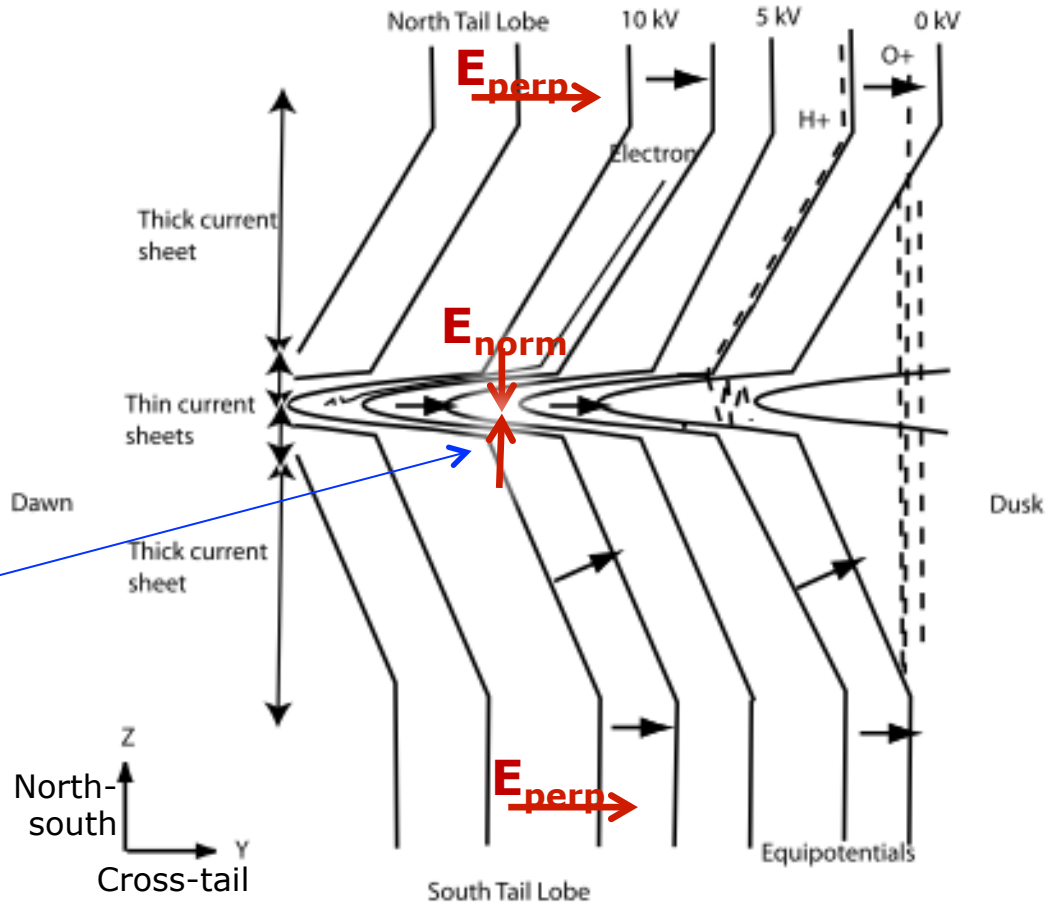
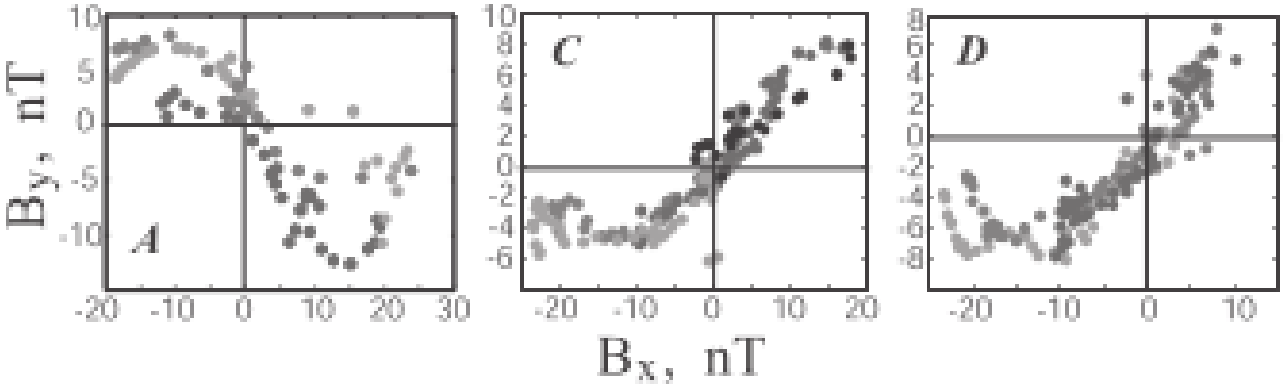
- Intense $\mathbf{E_{norm}}$ (±60mV/m) observed in the ion decoupling region. 4-6 kV potential drop
- Ballistic acceleration of ions.
- Evidence for accelerated ion beams by $\mathbf{E_{norm}}$.
- Ions accelerated by $\mathbf{E_{norm}}$

Electric equipotentials in YZ plane

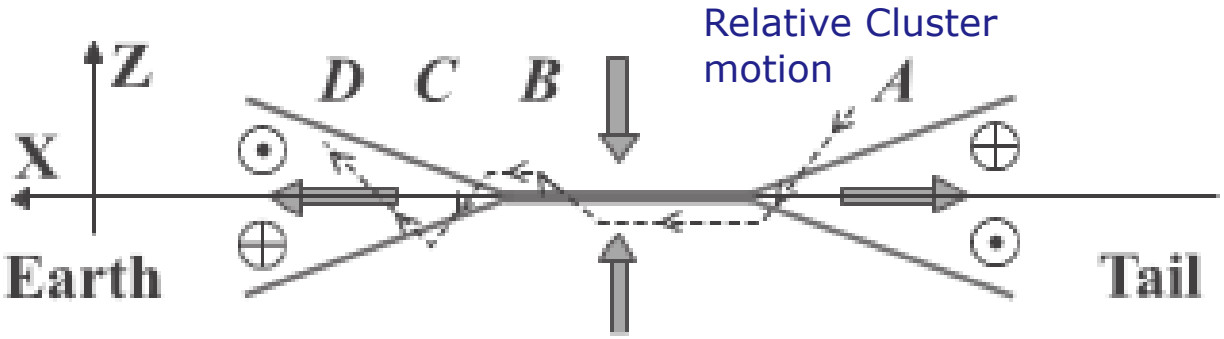


Example: October 1, 2001

- Specific event 09:47-09:51 UT also studied by Runov et al. [GRL, 2003].
- Observed: - Plasma jet reversals,
  - Bifurcated current sheet
  - Hall B_y at passages A, C, D
- Verified: current density can be computed with multi-spacecraft Curlometer method $J \sim \nabla \times \mathbf{B}/\mu_0$.



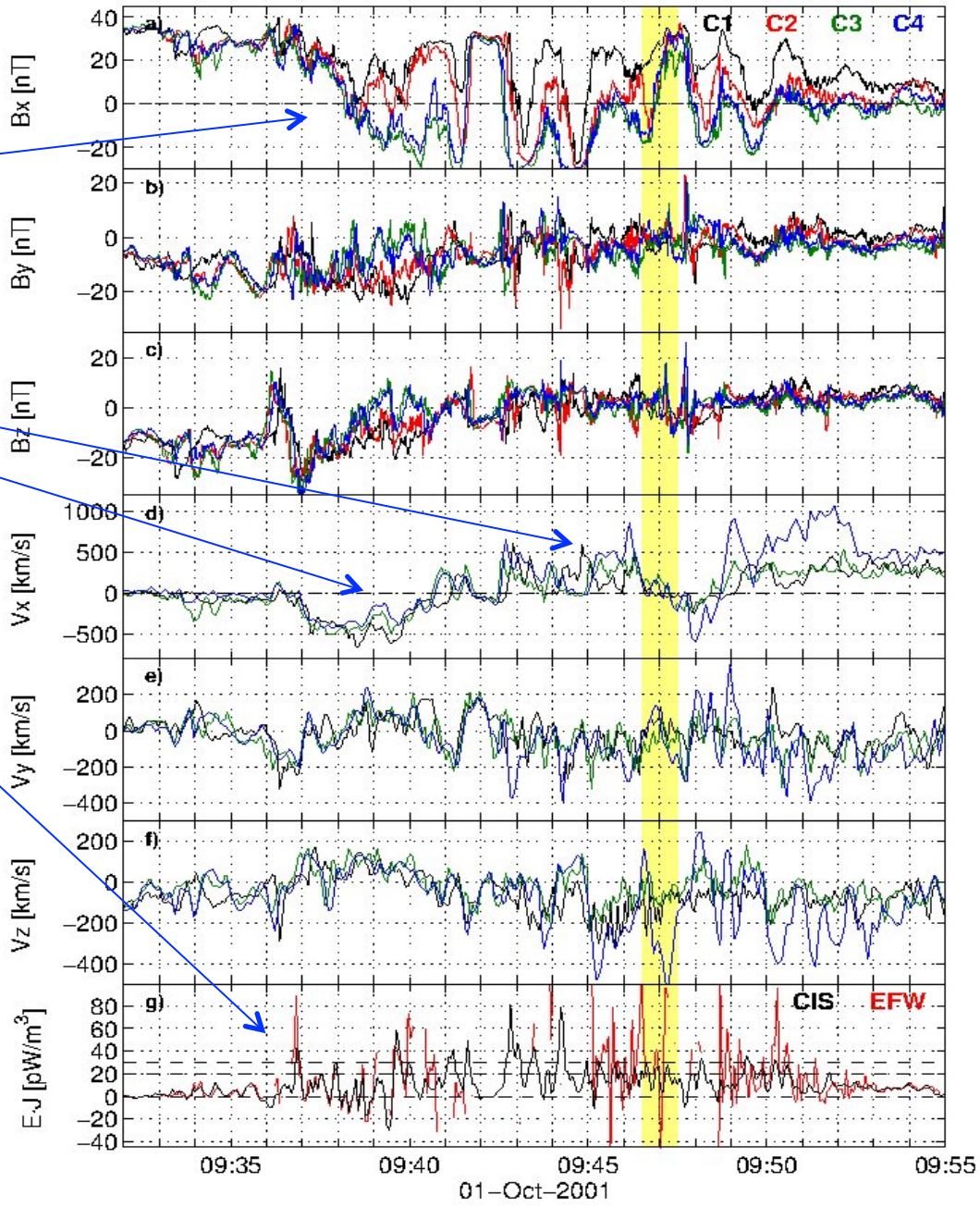
Hall By
(out of plane)



Relative Cluster motion

Details: October 1, 2001

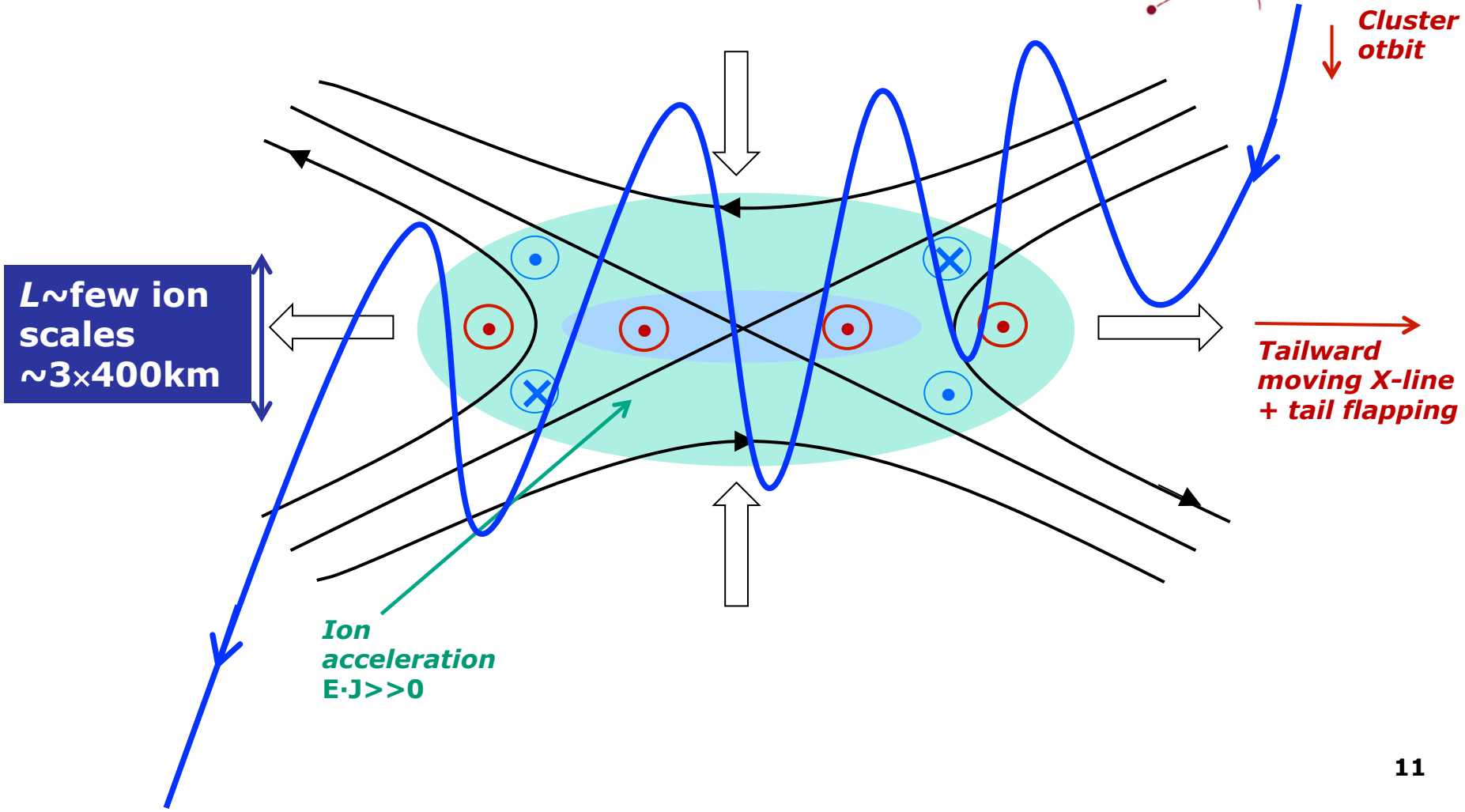
- Main Wygant and Runov event in yellow.
- Tail flappings
- Jet reversals
- Power density **E**·**J** using
  J from Curlometer and **E** from
  - CIS **E**~-**V**x**B** (frozen-in) [black]
  - EFW (direct **E** measurements) [red]
- **Power density is positive and large!**
- **E·J**>20 pW/m^3 in general.



Typical scenario

- Assume L~1200km
- V_{sat}~1km/s
- Time for Cluster to pass through diffusion region: T~L/V_{sat}~20min

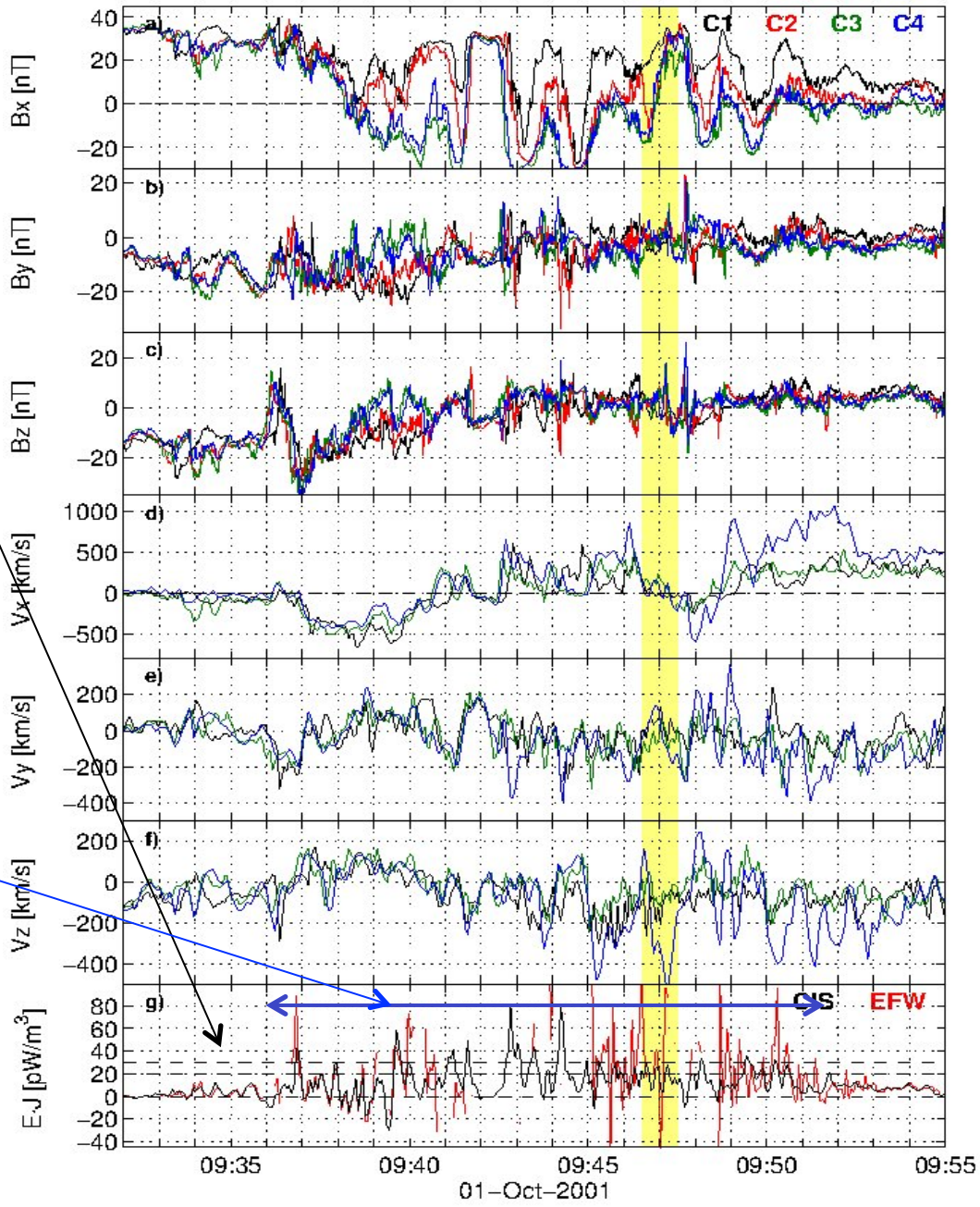
cluster



Recurrent Cluster sampling diffusion region

- Tail flappings → Recurrent Cluster observations of the diffusion region.

- Region with **E**·**J**>>0 is of the order of 20 min!



Can we trust the Cluster measurements?

- **Electric field:**

  - EFW:
  Direct measurements of **E**.
  Full vectors not always available.
  Cannot measure $\mathbf{E}_{para}$. (**E**·**B**=0)

  - CIS (HIA, CODIF):
  E=-**V**x**B** frozen-in condition.
  Generally available.
  Cannot measure $\mathbf{E}_{para}$.

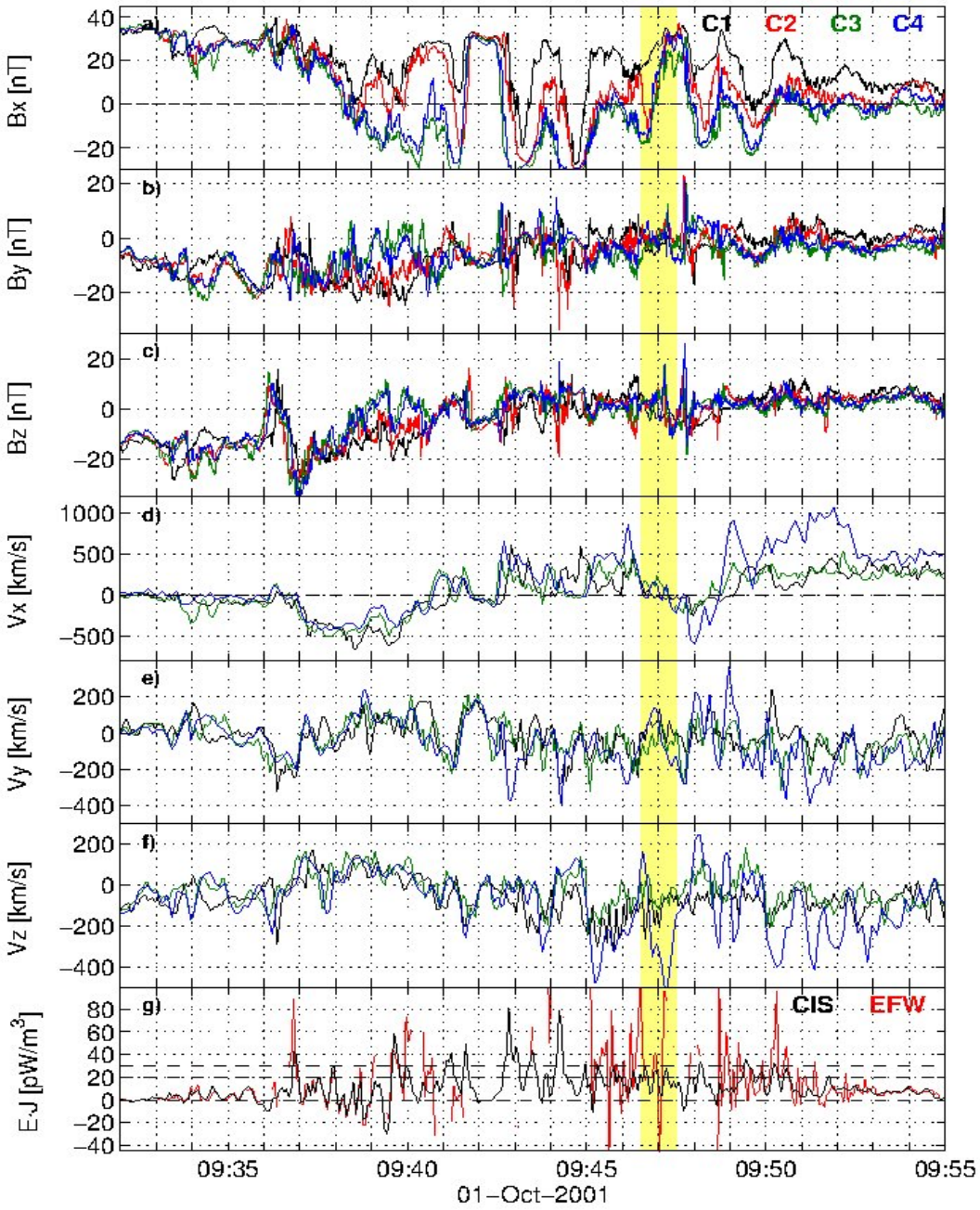
- **Current density:**

  - Curlometer:
  Generally operational. Simple to use.
  Smoothening: Resolves Cluster scales.

  - Single-spacecraft method:
  Only operational at current sheets.
  Higher resolution.

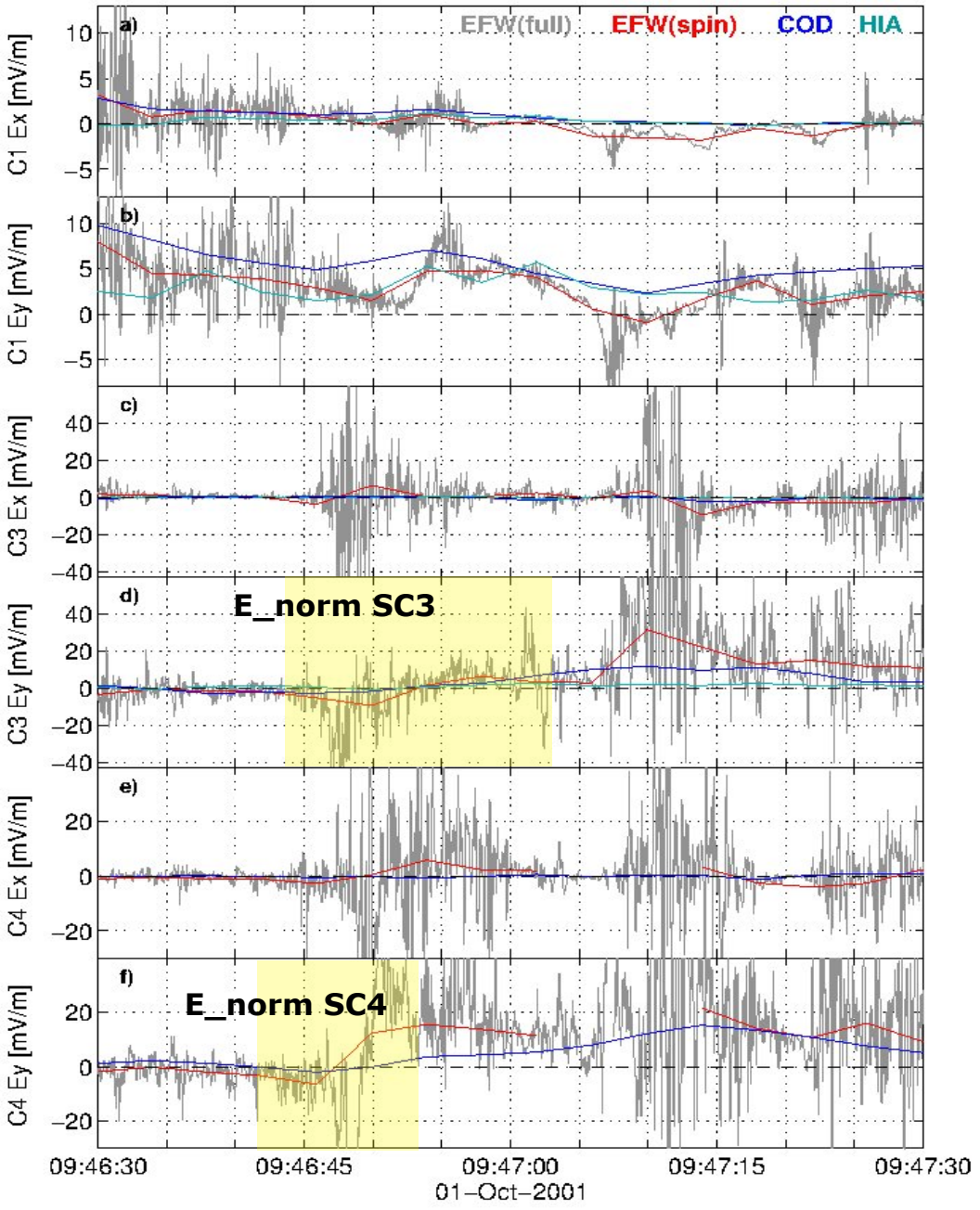
Improvements with MMS?

- 3D **E** field measurements.
- Smaller tetrahedron: more accurate Curlometer for small scale regions.



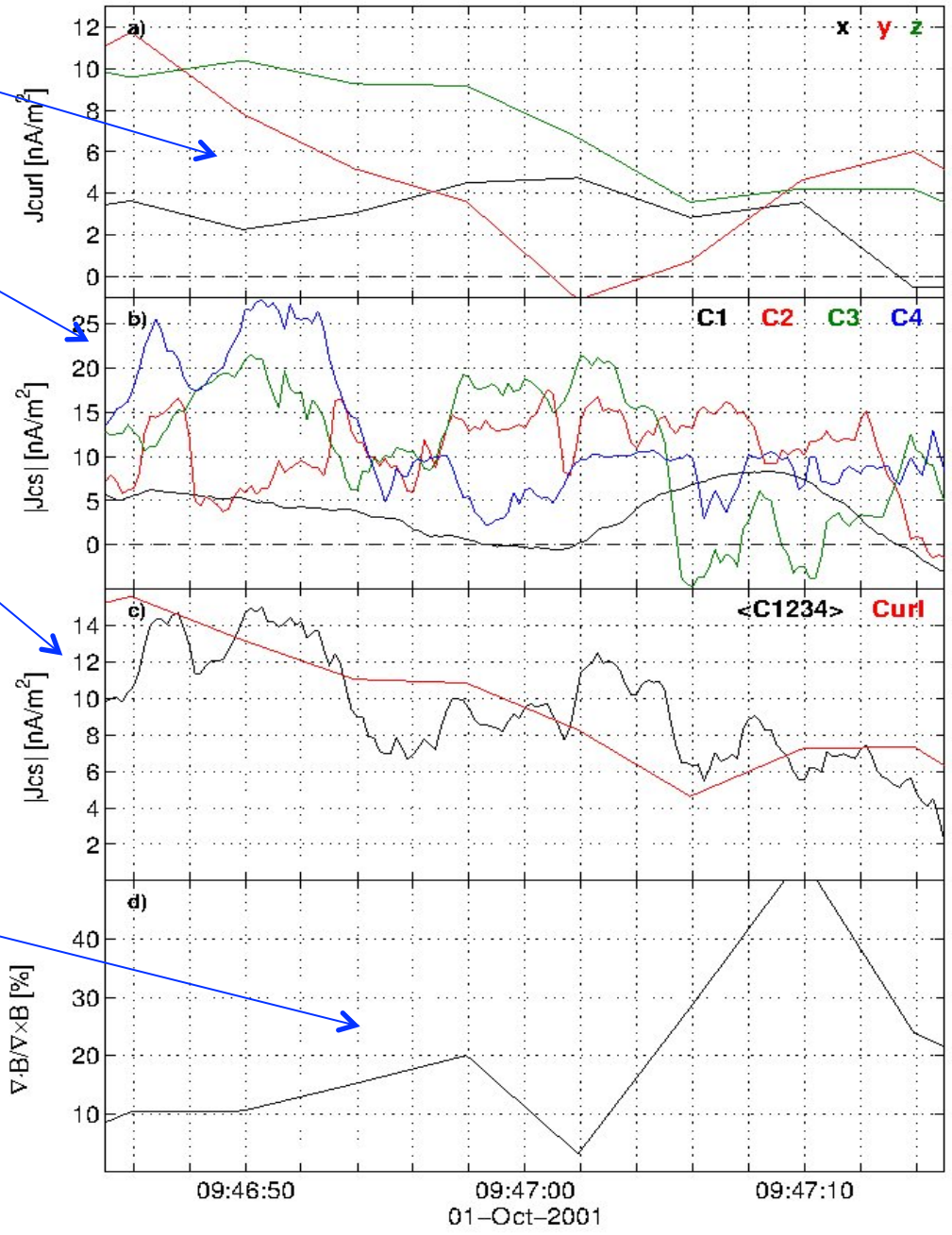
Cluster details: Electric fields

- October 1, 2001: Main Wygant and Runov event in yellow.
- Full resolution **E** (25Hz) from EFW [**gray**]
- CIS **E** [**blue**/**cyan**] underestimates EFW spin-averaged estimate [**red**] but follows general trend.
- **Qualitative agreement.** Same sign.



Cluster details: Current densities

- Multi-spacecraft Curlometer $\mathbf{J} \sim \nabla \times \mathbf{B}/\mu_0$.
- Single-spacecraft currents (5vec/s).
- Cross-tail Curlometer current [**red**] and single-spacecraft current averaged over C1234 [**black**].
- Curlometer and single-spacecraft estimate are consistent!
  But Curlometer is more smooth.
- Curlometer quality estimate, $\nabla \cdot \mathbf{B}/\nabla \times \mathbf{B}$, is generally small.
- **Curlometer method can be used.**
  (cf. Runov 2003).
- **Qualitative agreement.** Same sign.

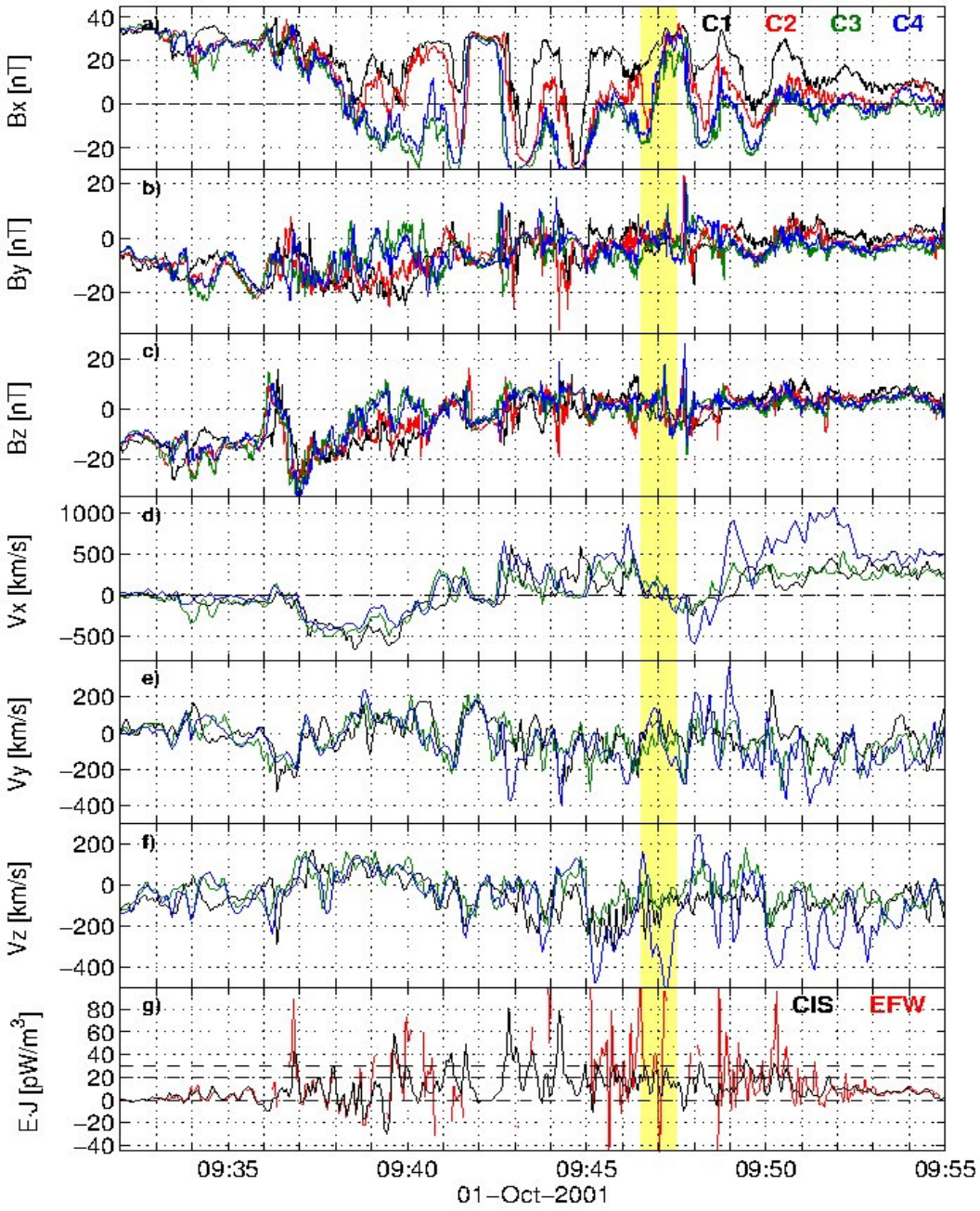


Recap: The reconnection load

- Using the Culometer **J** and CIS **E**=-**V**x**B** we find that **E**(CIS)·**J**(Curl)>>0 (>~20 pW/m^3).

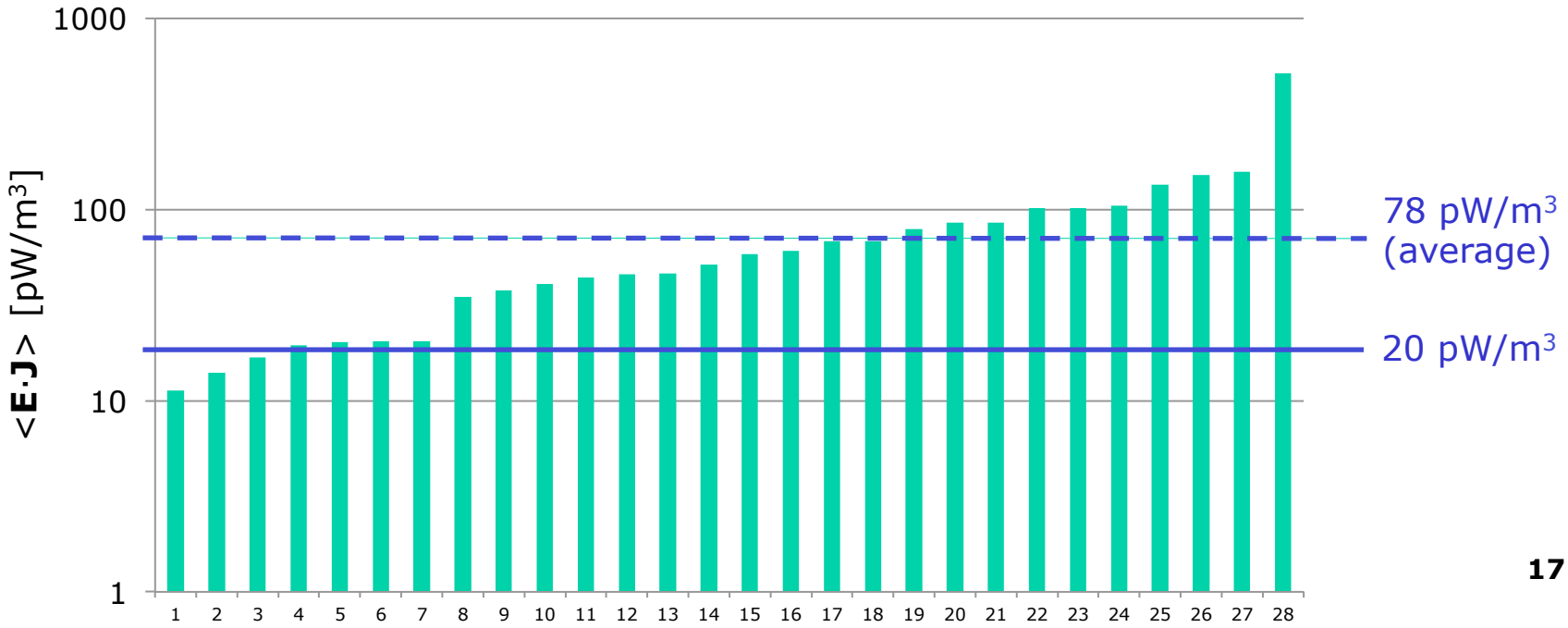
- |**E**(CIS)| < |**E**(EFW)|, same sign
- |**J**(Curl)| < |**J**(1-sc)|, same sign

- "True" **E**·**J** is possibly even larger than ~20 pW/m^3.



Statistical investigation

- Cluster observations 2001.
- 28 documented Cluster reconnection events in the literature:
  Borg et al. [Ann. Geophys. 2012], Eastwood et al. [JGR 2010], Østgaard et al. [JGR 2009].
- $-14<X_{GSM}\leq-19R_E$, $|Z_{GSM}|\leq3.5R_E$, $|Y_{GSM}|\leq10R_E$ (except 2 events slightly outside).
- $\mathbf{E}\cdot\mathbf{J}>20pW/m^3$ using CIS **E** (3 events lightly lower).
- **E·J** generally >>$20pW/m^3$ when using EFW **E**. (But full EFW **E** not always available.)



Additional Cluster events 2001

- 14 additional magnetotail reconnection events (or multiple events) found when searching all 2001 Cluster data.
- Cluster data 2002-2004 can also be scanned, but in >2005 Cluster is in multiscale mode. (But more care needed due to successive instrumental degradations.)

Event	Date	T_1	T_2	$\mathbf{X}/\mathbf{Y}/\mathbf{Z}$ $[R_E]$	Max $\mathbf{E}\cdot\mathbf{J}$ $[\mathrm{pW/m^3}]$ CIS/EFW	Samples $\mathbf{E}\cdot\mathbf{J} > 20$ CIS/EFW	Reconnection?	Comment
1	2001-08-03	10:40	11:15	-17/-8.5/2.2	48/48	38/21	Yes	
2	2001-08-05	13:00	14:10	-17/-7.8/5.7	35/27	6/4	Can be	Several sub-events
3	2001-08-07	23:40	00:05	-17/-8.4/2.1	28/38	6/7	Yes	
4	2001-08-12	17:00	18:50	-18/-6.7/3.1	54/47	47/27	Yes	Several sub-events
5	2001-08-17	13:00	15:00	-18/-4.7/2.6	114/71	55/77	Can be	Several sub-events
6	2001-08-31	17:10	17:20	-19/-0.8/2.5	51/79	9/10	Yes	
7	2001-09-02	23:45	00:35	-19/-0.7/3.5	30/26	2/3	Yes	Several sub-events
8	2001-09-07	21:30	22:00	-19/1.2/1.1	21/27	2/4	Yes	
9	2001-09-12	15:10	15:16	-19/2.8/0.5	36/27	3/3	Yes	
10	2001-09-15	03:49	04:35	-19/3.5/-2.0	56/47	44/10	Yes	Several sub-events
11	2001-09-24	00:10	00:20	-14/3.4/ 7.2	30/NaN	5/-	Can be	
12	2001-09-26	22:20	23:10	-18/7.1/-0.4	25/59	2/7	No	
13	2001-10-01	11:40	11:50	-17/8.0/-0.4	26/49	17/24	Can be	
14	2001-10-08	14:40	14:50	-16/9.7/-0.3	28/24	2/2	Can be	

Summary and conclusions

- Regions of strong and localized energy conversion may be used as an indictor for magnetic reconnection:
  E·**J** as a method for identifying potential reconnection events from large amounts of measured spacecraft data.

- Signatures should be verified manually by investigating e.g. jet reversals and Hall fields.

- Criterion for tail reconnection: **E**·**J** is large (>~20 pW/m^3 consistent with theoretical arguments).

- **E**·**J** easily computed from multi-spacecraft data, e.g. MMS and Cluster.
  - **J**: Curlometer method
  - **E**: ion moments –**V**x**B** (e.g. CIS) or direct measurements (e.g. EFW)

- From a statistical investigation using already documented events (Cluster 2001) we find:
  - **E**·**J**>~20 pW/m^3 using CIS ion moments
  - **E**·**J** generally >>20 pW/m^3 using EFW measurements.

- Several additional events found when scanning all Cluster plasma sheet data from 2001.

Thank you!

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