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Multi-scale analysis of dayside reconnection and Swarm-Cluster coordination.

M W Dunlop

[Thanks to: J-S He, C-L Xiao, Q-H Zhang, Z-Y Pu, C Shen, Y Bogdanova, H. Luhr, N. Olsen, Y-Y. Yang, J-B Cao, P Escoubet, K. Trattner, A N Fazakerley, A. Masson, J-K Shi.]

- Electron (FA) signatures near a high-latitude X-line
- Active reconnection across wide local time
- Cluster-Swarm coordinated multi-spacecraft analysis (FA-currents)

Cluster-Double Star conjunction: Onset of high latitude MR?

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Cluster ~1500 km, ion-inertial ~70 km; BL ~2-3000 km.

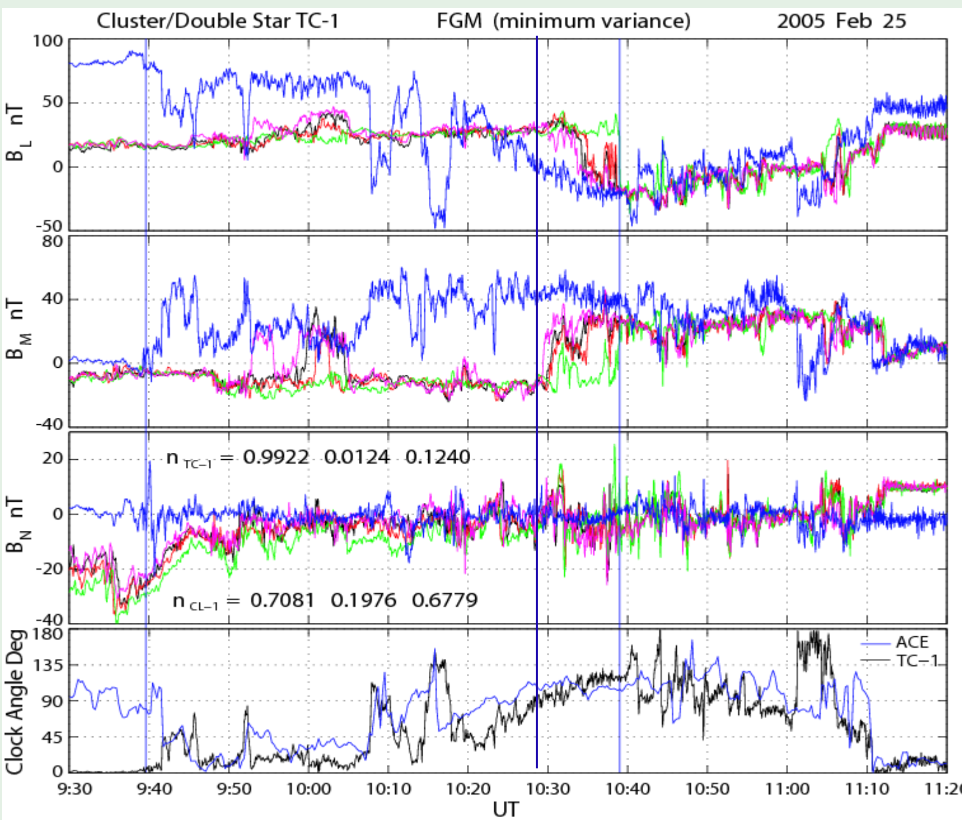
Follows active low latitude MR at TC1.

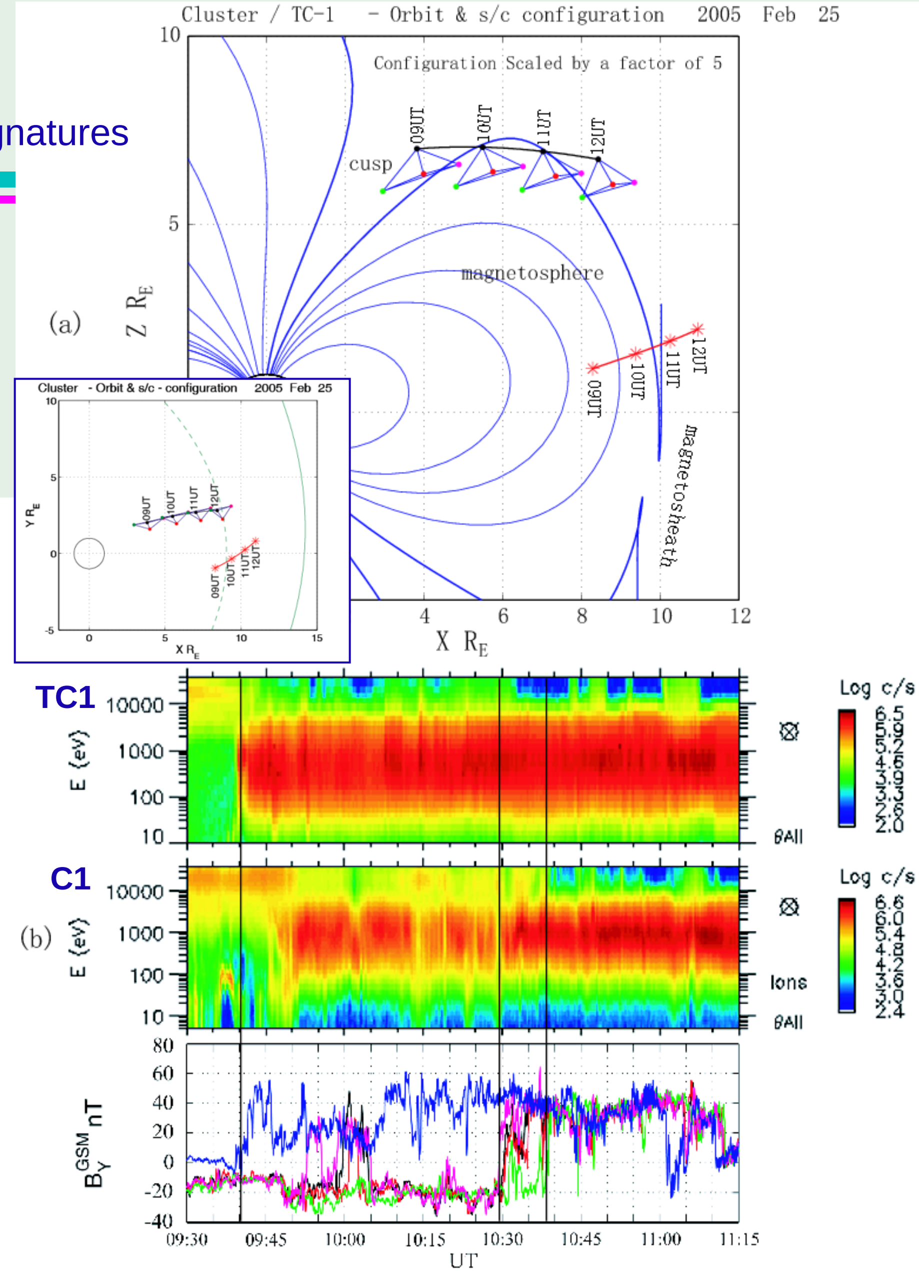
Electron data shows: energised field aligned signatures

Variable N/S IMF under strong By. TC1 - northward FTEs: TC1 initially north, then south of x-line…

Cluster exits through the dayside plasma sheet, grazing south of the cusp (ion data): not lobe reconnection.

Last, slow BL exit at MP (1-2 km/s): Cluster FTEs are northward/eastward; polarity unclear after 10:30 UT.



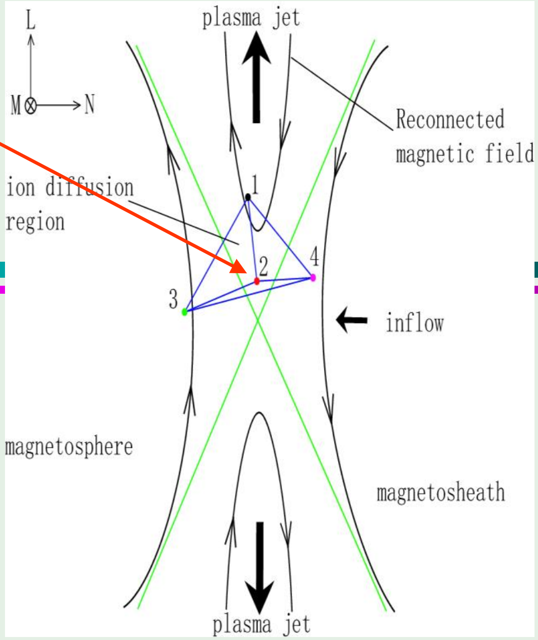


Magnetosheath crossing: Cluster direct sampling of X-line?

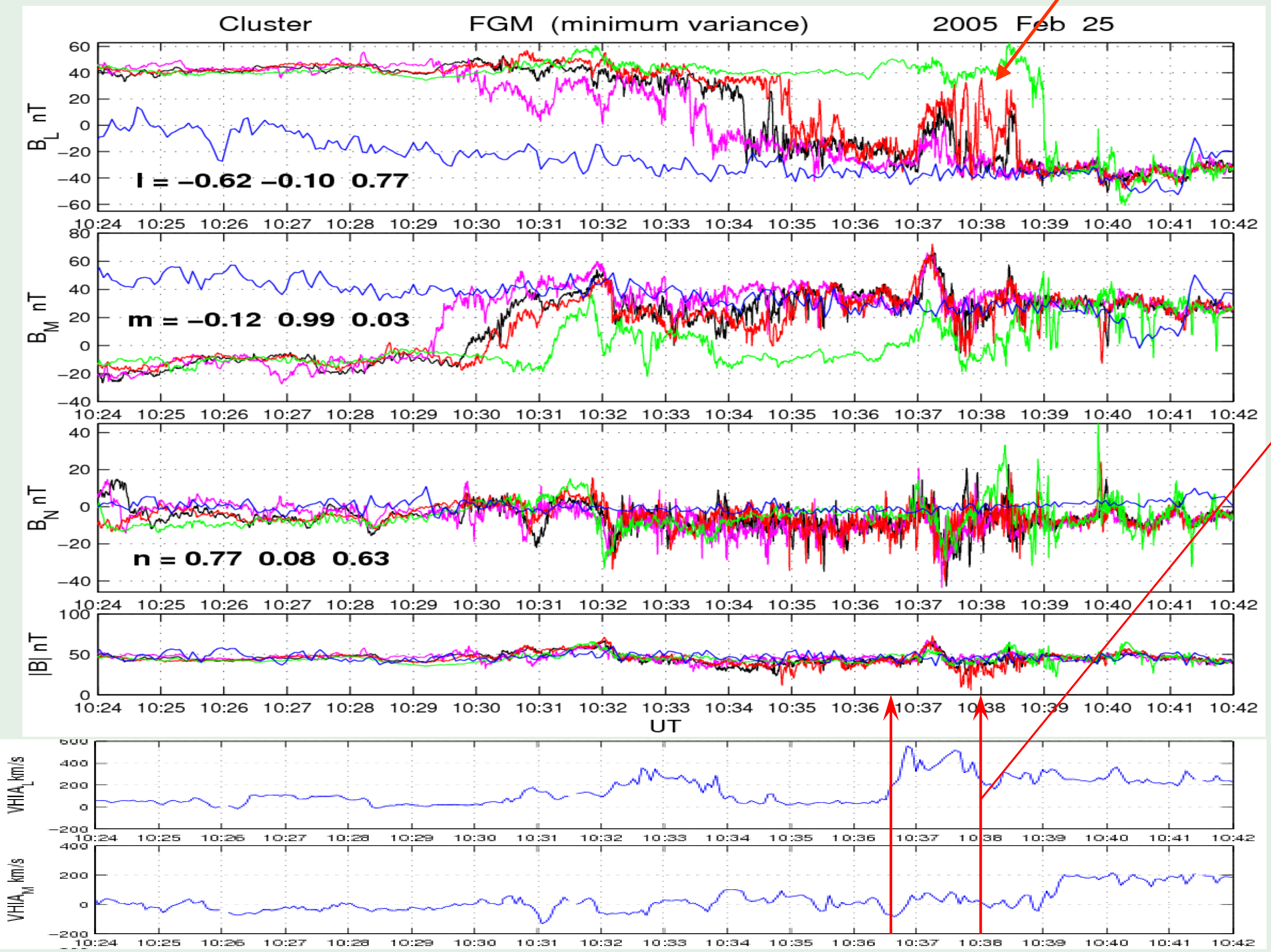
C2 sees multiple reversals of B_L; (C1,C4 see 2 reversals); C3 in magnetosphere.

Consistent with anti-parallel reconnection site.

Possible secondary X-line formation during low latitude MR?



Single scale at Cluster suggests a persistent structure, with small relative motion taking the spacecraft in and out of region.



- Reconnection ion jet: BL aligned flow bursts consistent with reconnection layer. (C3)
- Walen test confirms reconnection induced stress, for a By dominated configuration
- Evidence of Hall signature in BM bipolar signature:

Size of the M component signature is on the scale of the spacecraft separation ~1000 km (cf. Ion inertial length ~70 km).

Cluster direct sampling of X-line:

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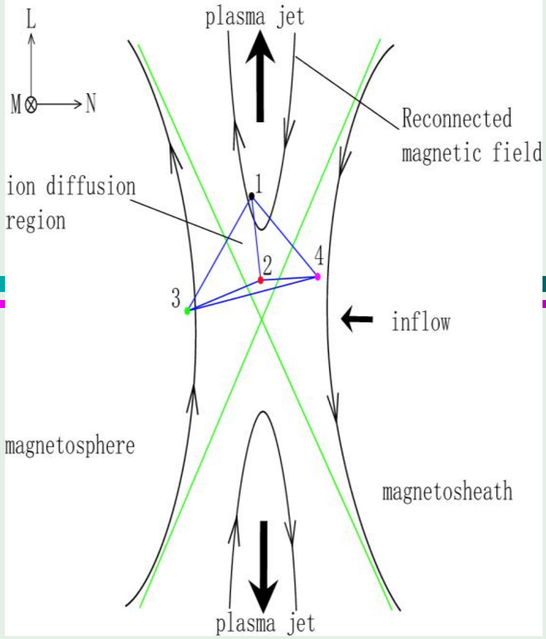
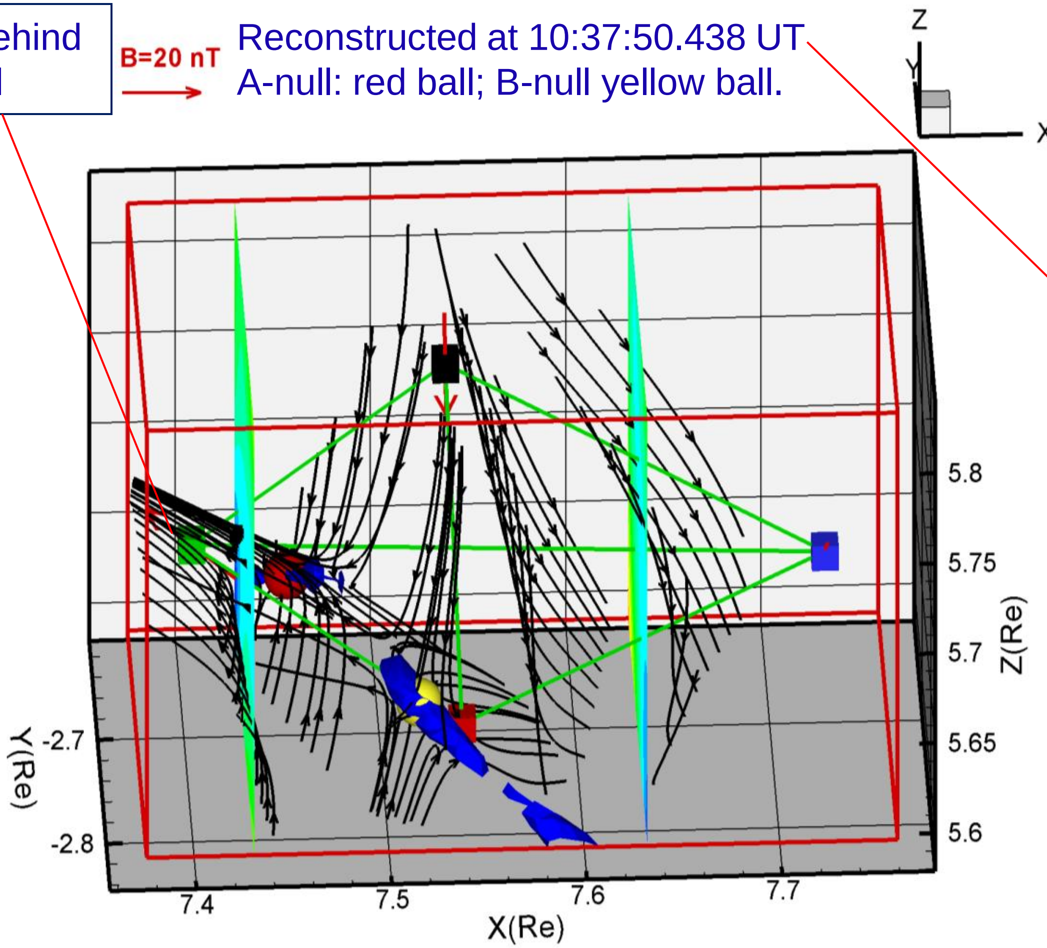
Poincare index test of X-line null field encounter: magnetic (type A) nulls found

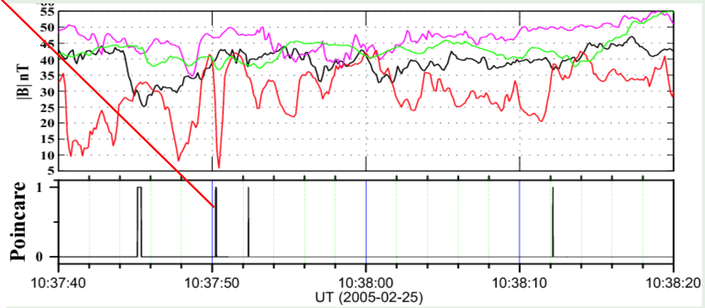
Occurs during dropouts in |B| at C2: |B|<10 nt (min = 5nT)



C3 behind A null

Reconstructed at 10:37:50.438 UT
A-null: red ball; B-null yellow ball.





- Field line reconstruction inside the Cluster tetrahedron shows a clear A-B, null-null
- Confirmation of nearby X-line structure where B-null lies just outside Cluster; close to C2. C3 lies behind A null.

[Previous reconstructions in magnetotail are not so sensitive, *He et al*. 2007]

Note: A-B pair is sensitive to reconstruction origin, but X-line persists also at other null encounters(X-line orientation is affected).

Cluster direct sampling of X-line:

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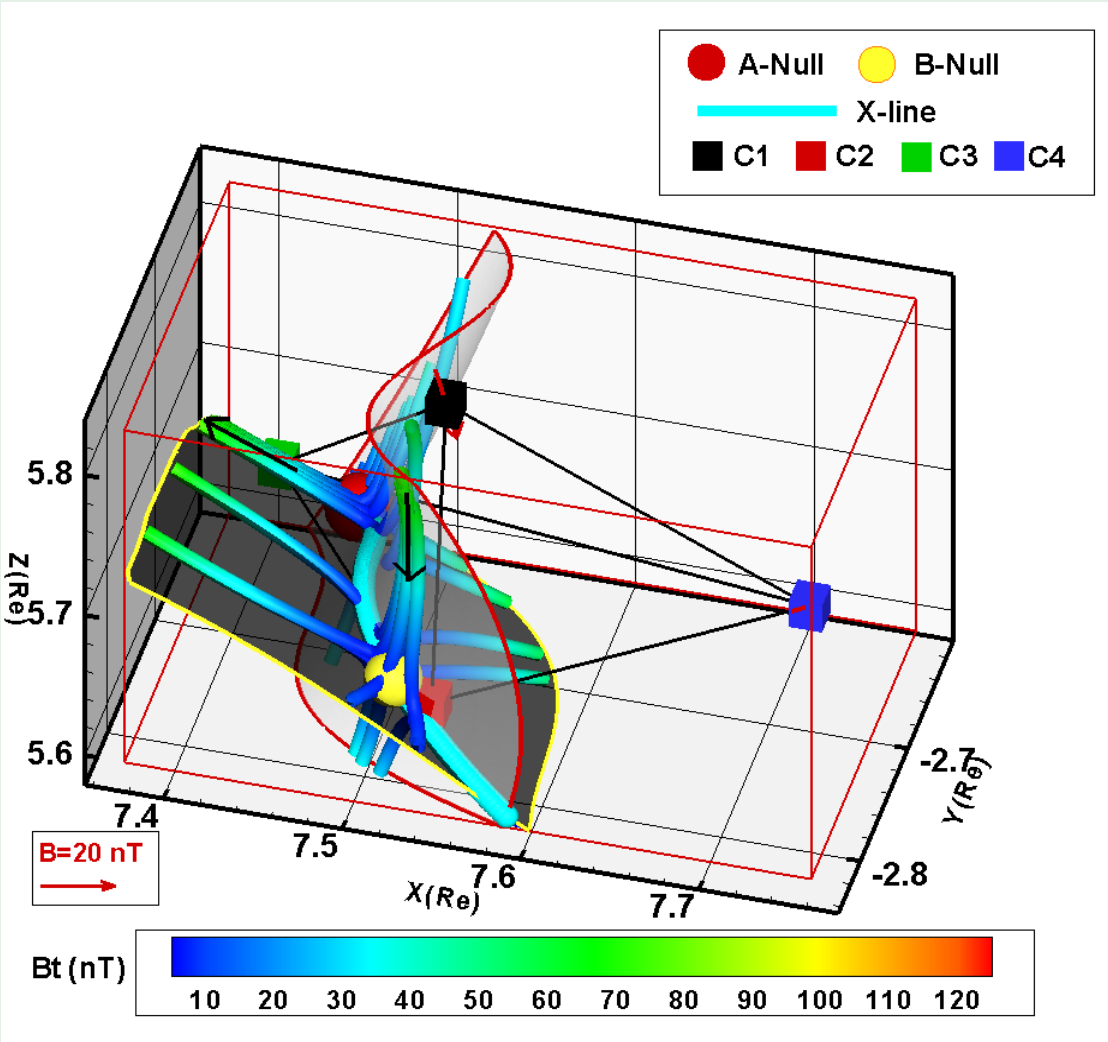
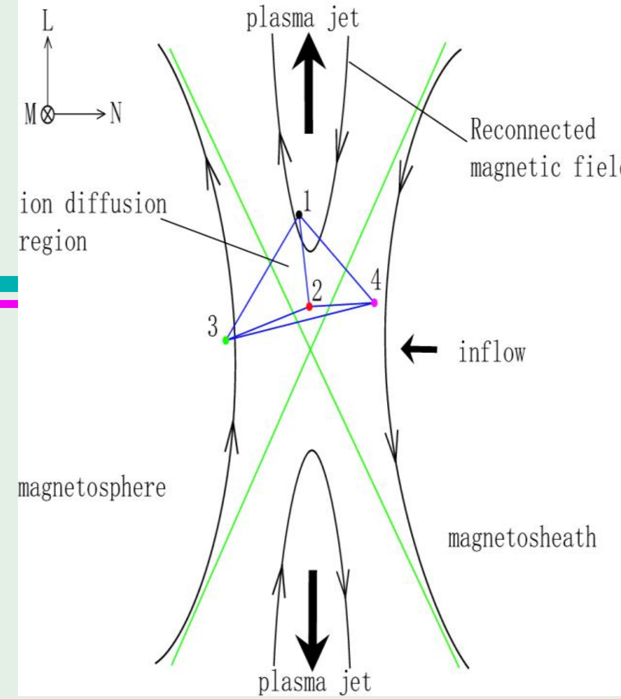
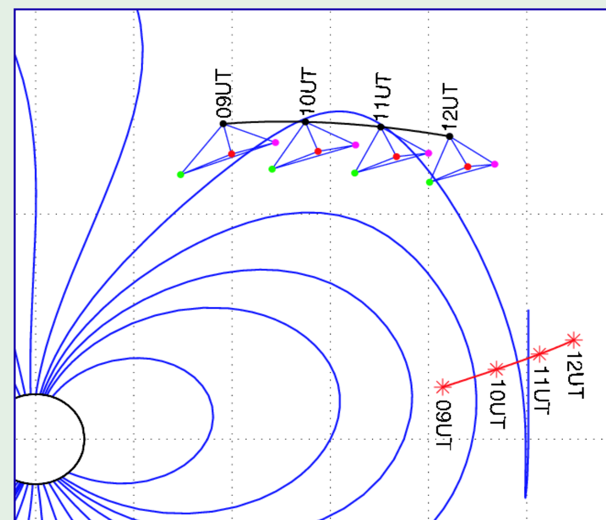
Reconstruction of 3-D A-B structure [*He et al.*]

B-null lies just outside the Cluster; close to C2







Electron data: 25 Feb 2005

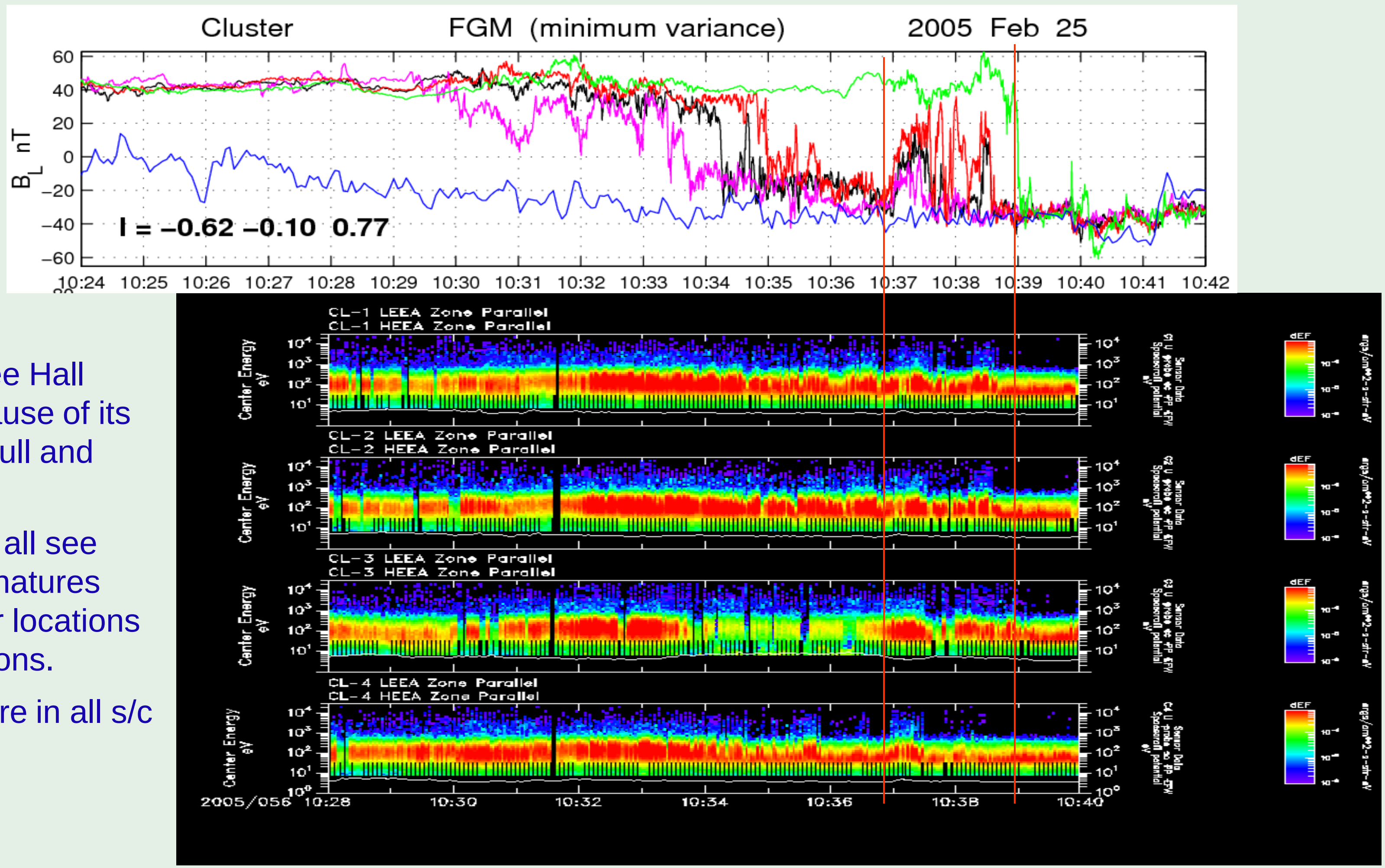
Shows complex FA and trapped populations consistent with diffusion region encounter

Always ‘north’ of the X-line; C3 in depleted region of magnetospheric layer: but just outside A null

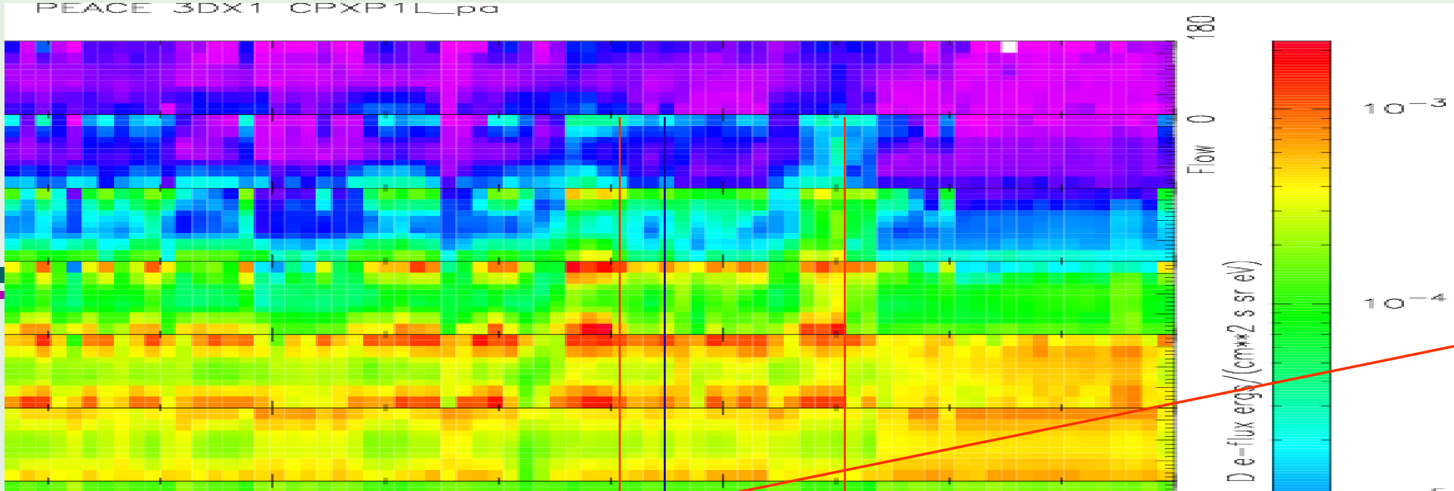
Expect C2 to see Hall signatures because of its proximity to B-null and central location.

C1,C3,C4 may all see different ion signatures because of their locations in adjacent regions.

Electron structure in all s/c



Ion & electron data: Cluster 1

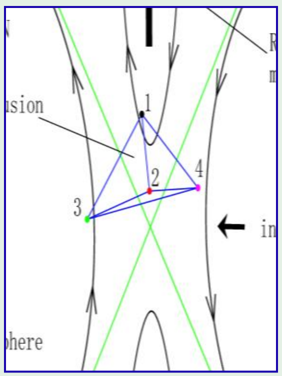


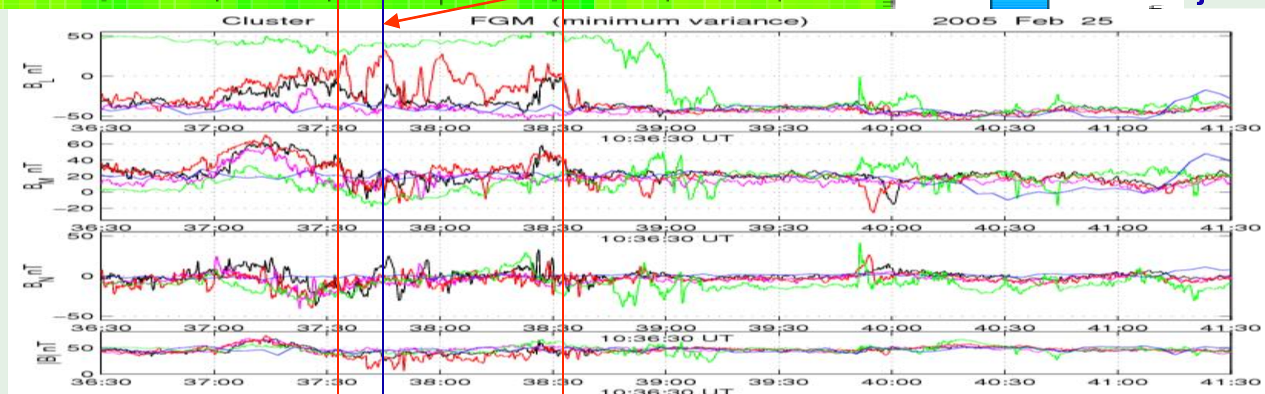
@ Null field: C1 just north of x-line.

Strong northward ion jets.

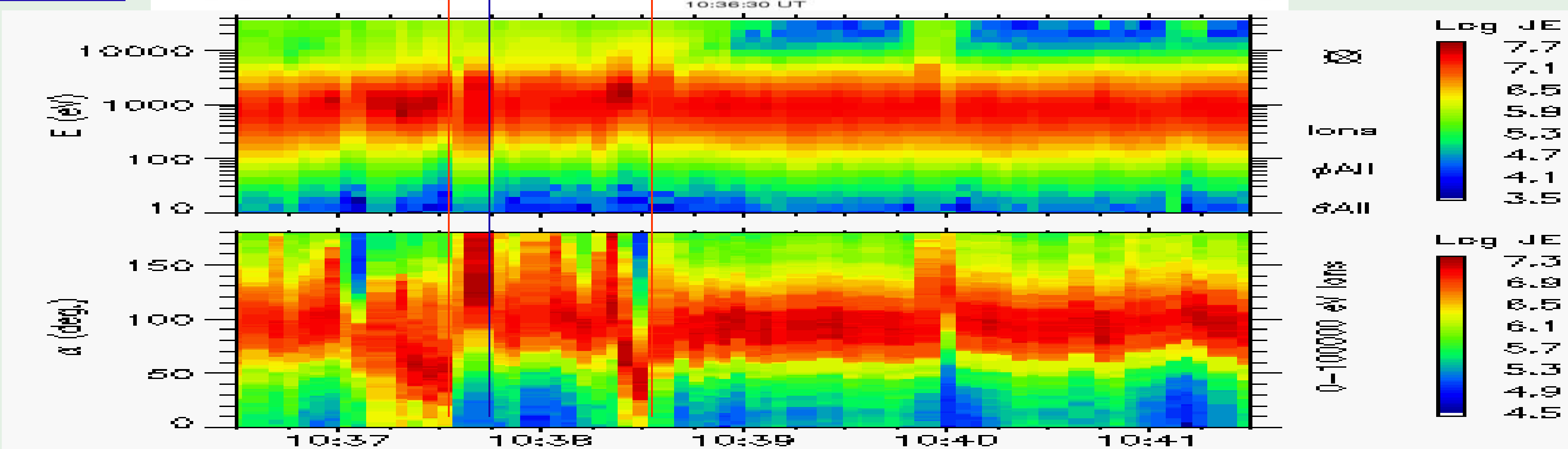
electrons:

reversing FA beams





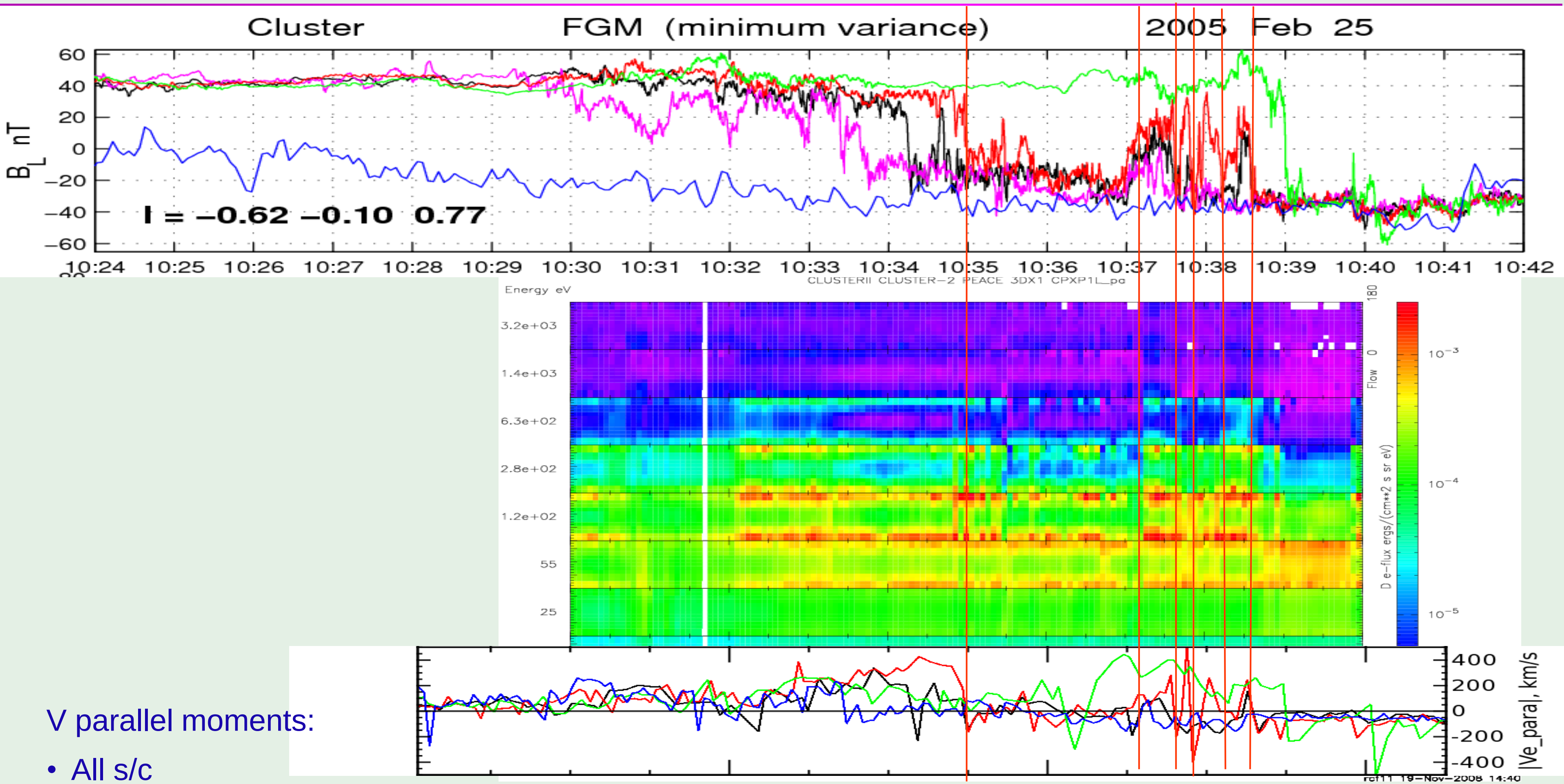
Other s/c consistent with their relative locations.



Electron data: s/c 2

Note that PEACE is in 3DX mode giving 4 sec average moments from LEEA+HEEA data

Electron beams seen in pitch angle distribution and show as V-parallel moments in C2.



V parallel moments:

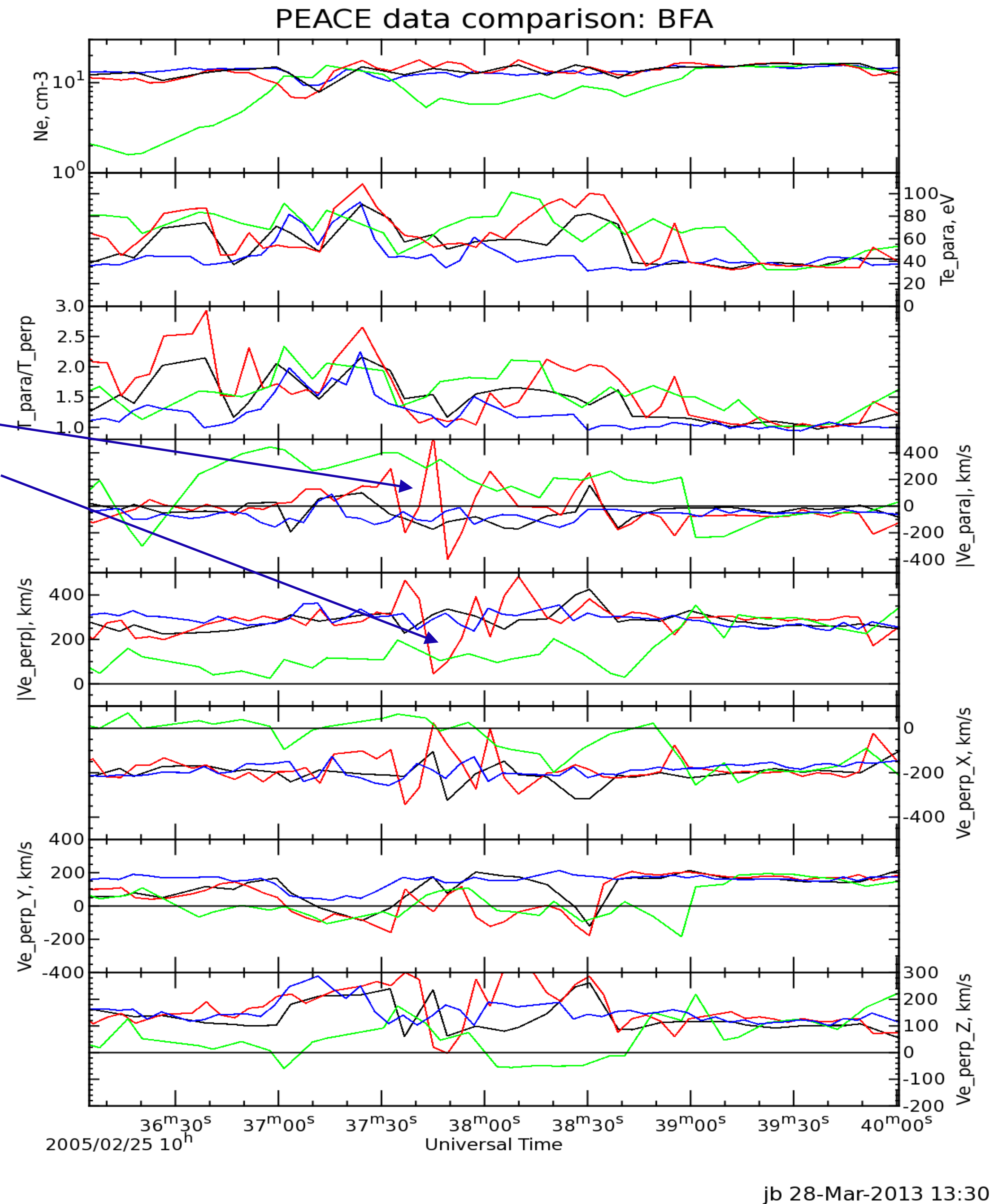
- All s/c
- C2 reversals correspond to B_L direction: sampling of seperatrix region.

Electron data: moments

All spacecraft data

Shows that:

- C2 is closest to B-null
- sees reversing FA electron flows
- V-perp drops to near zero at same time
- Consistent with bursts of Hall currents
- Reversals only seen on C2.
- Expect other spacecraft to surround core region.



High-latitude X-line conclusions

•Shown good evidence of a high latitude dayside magnetic reconnection:

-shows change in reconnection from low to high latitudes under variable IMF

-possible formation of secondary X-line during active low latitude MR

• Confirmation of encounter with X-line structure:

-Null field identification and MFL reconstruction within the s/c tetrahedron.

-Particle distributions consistent with s/c locations relative to 3-D A-B null pair

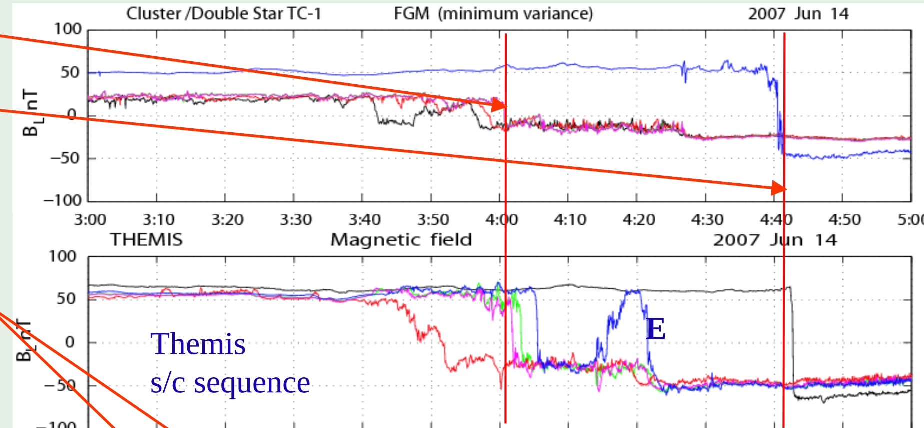
-Electron flows show pure FA beams for inner s/c close to null field

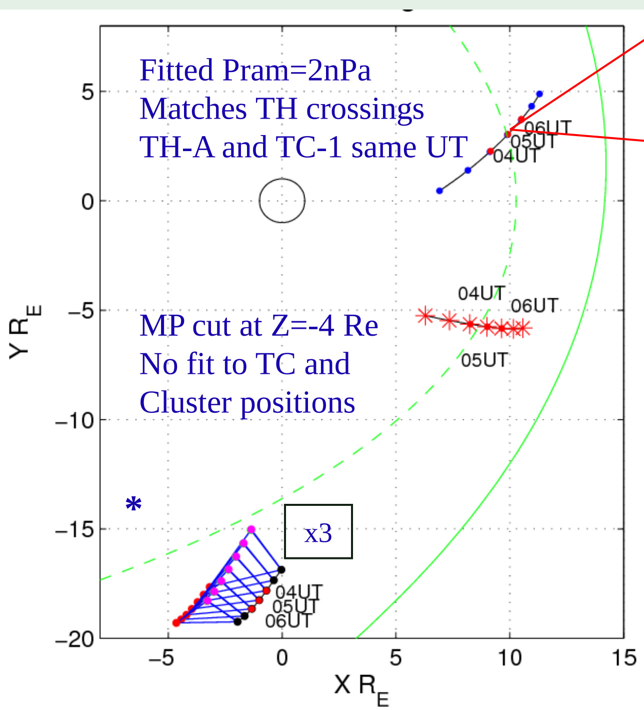
Multi-scale analysis through Themis-DSP-Cluster coordination:

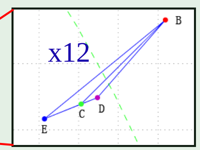
[*Dunlop et al., Phys. Rev. Letts., 2011, Ann. Geo. 2011*]

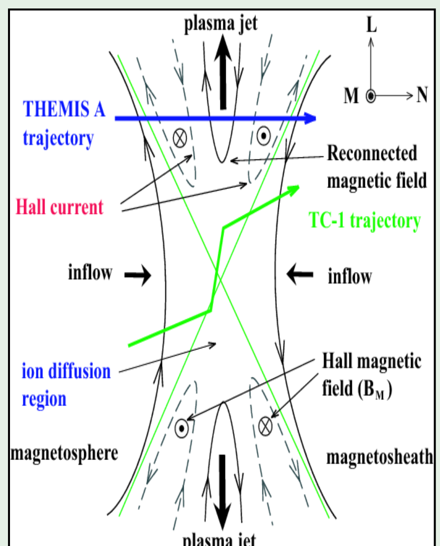
- First large scale (dawn-dusk) sampling across the magnetopause: **unique database**
- Close conjunction of10-s/c: produces near simultaneous MP crossings to probe multiple MR sites

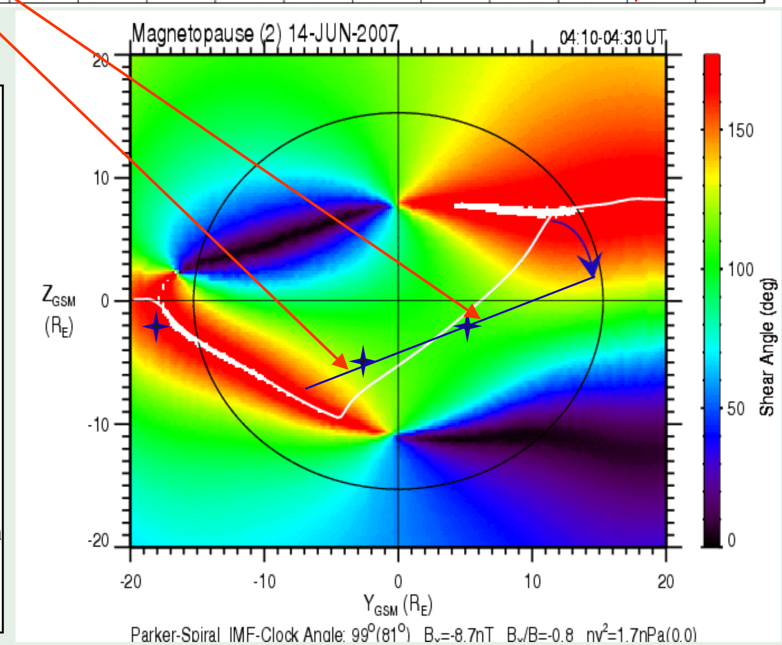
- Cluster and Themis arrays first exit close together, followed by TH-A and TC-1.
- Cluster remains close to a flank anti-|| site
- Fast MP exits (MP compression) at TH-A and TC-1
- **First direct, simultaneous sampling of component driven reconnection** at widely separated (10 Re) sites.











14 June: TC-1 and TH-A crossing

Both very near and north of X-line

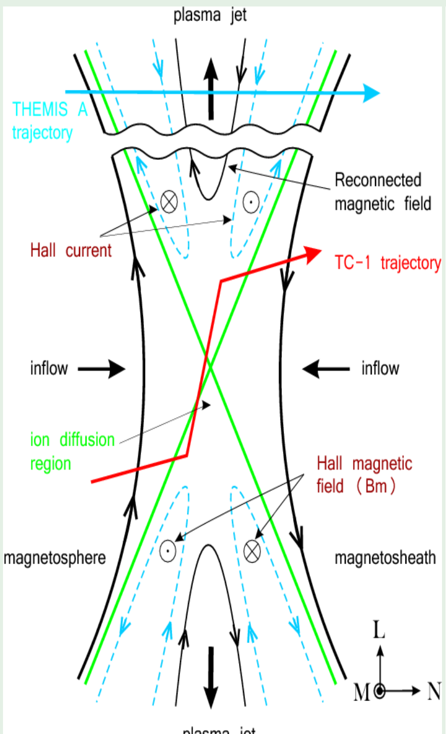
dB/dt and electron moments suggest possible hall current signatures

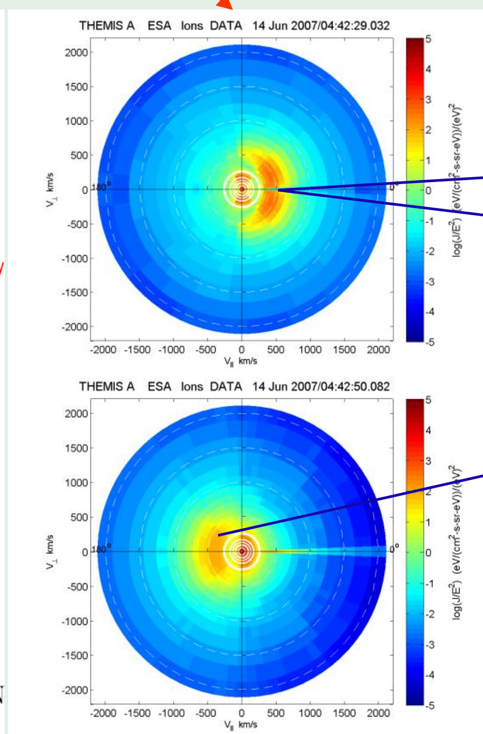
Accelerated ions along B-field: reflected and transmitted by the current layer ($E_{||}$=4xE_{SH}).

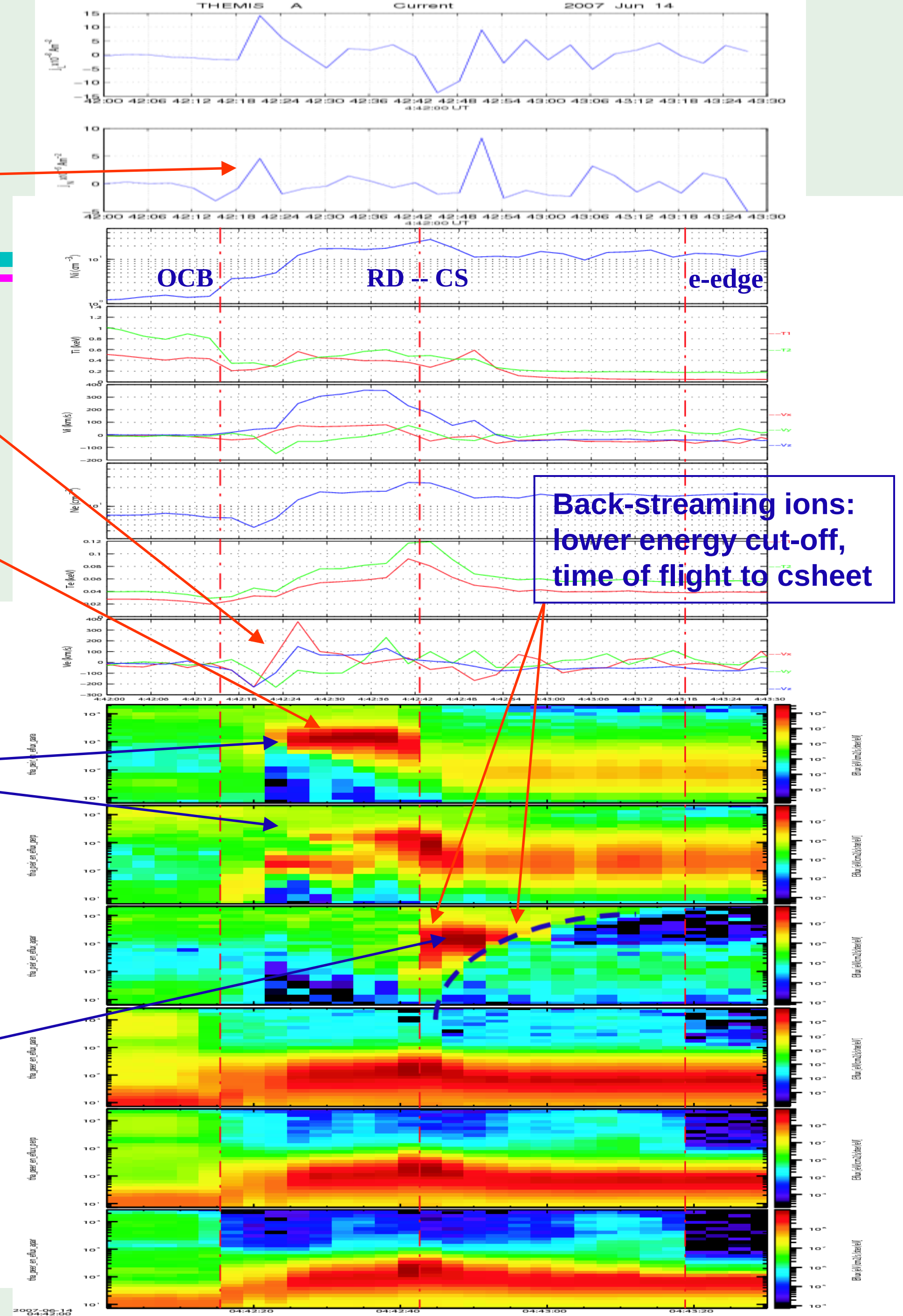
Show energised incoming m'sheath

Ions show 'Cowley' D-distribution.

Additional populations exist.





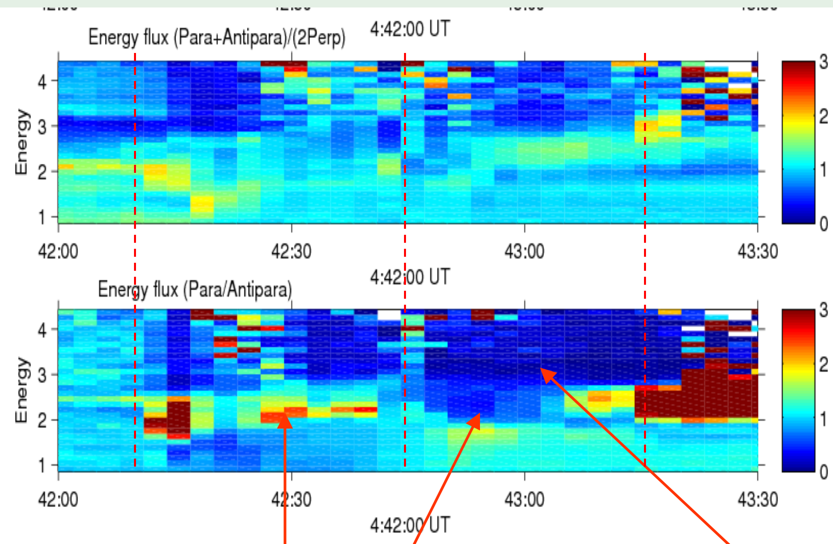


14 June: TC-1 and TH-A crossing at 4:40-4:42 UT.

Electron anisotropy shows bi-streaming, then out-flowing populations at OCFLB.

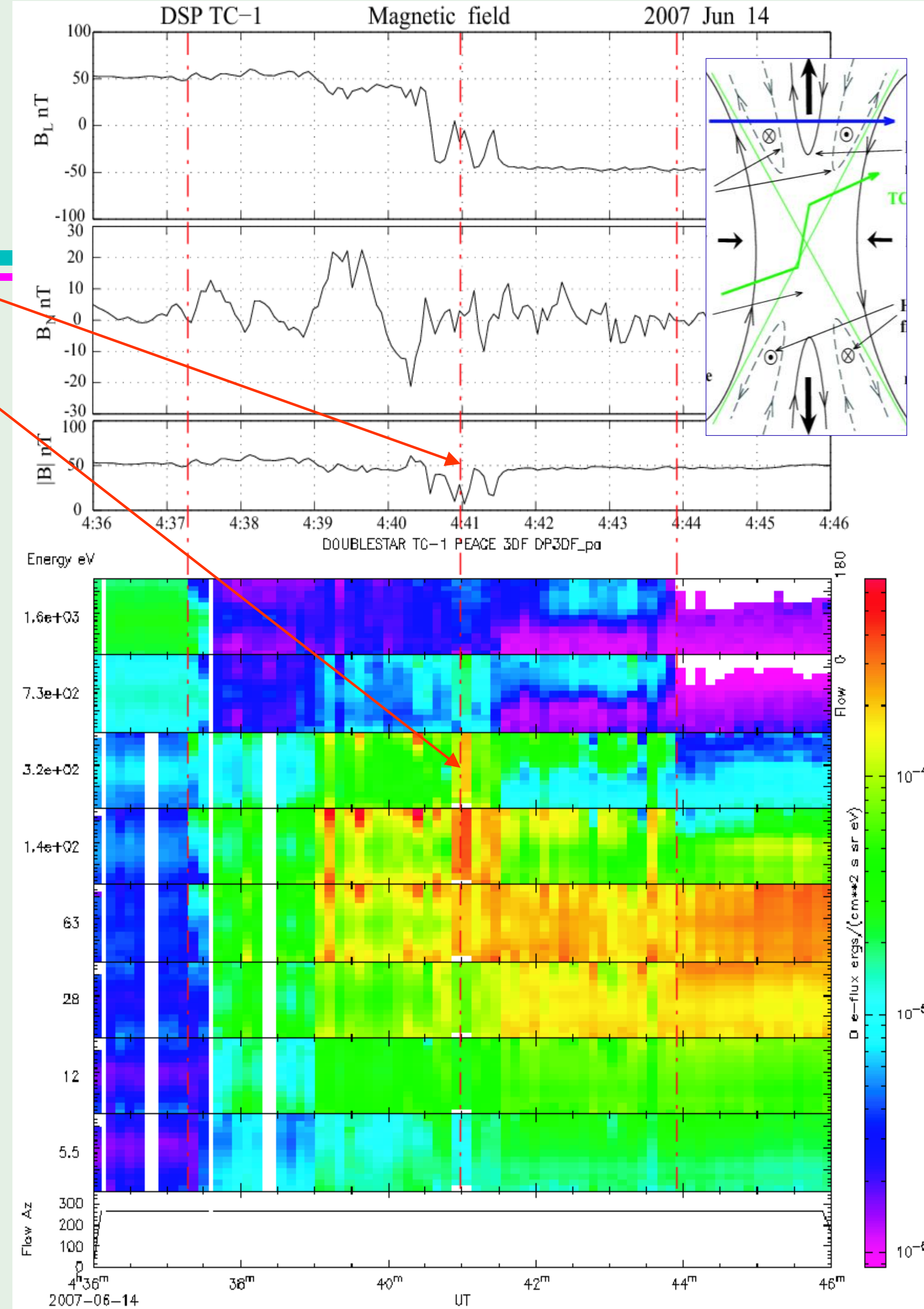
TC-1 lies almost in null field region

Themis-A electron distribution shows only a small anisotropic component, so no strong field aligned flux (top panel below).



and an incoming/ backstreaming magnetosheath electrons either side of the current layer.

The field aligned electrons do show out-flowing magnetospheric populations in reconnection layer,

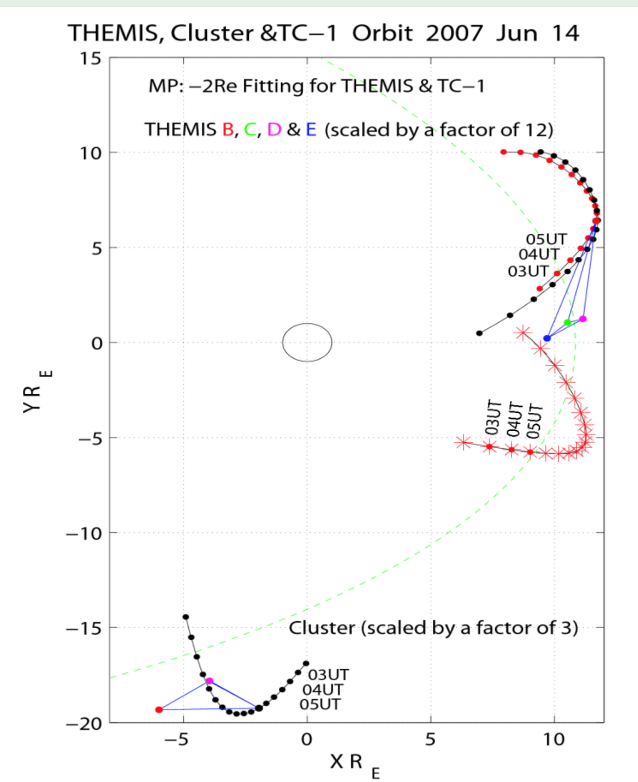


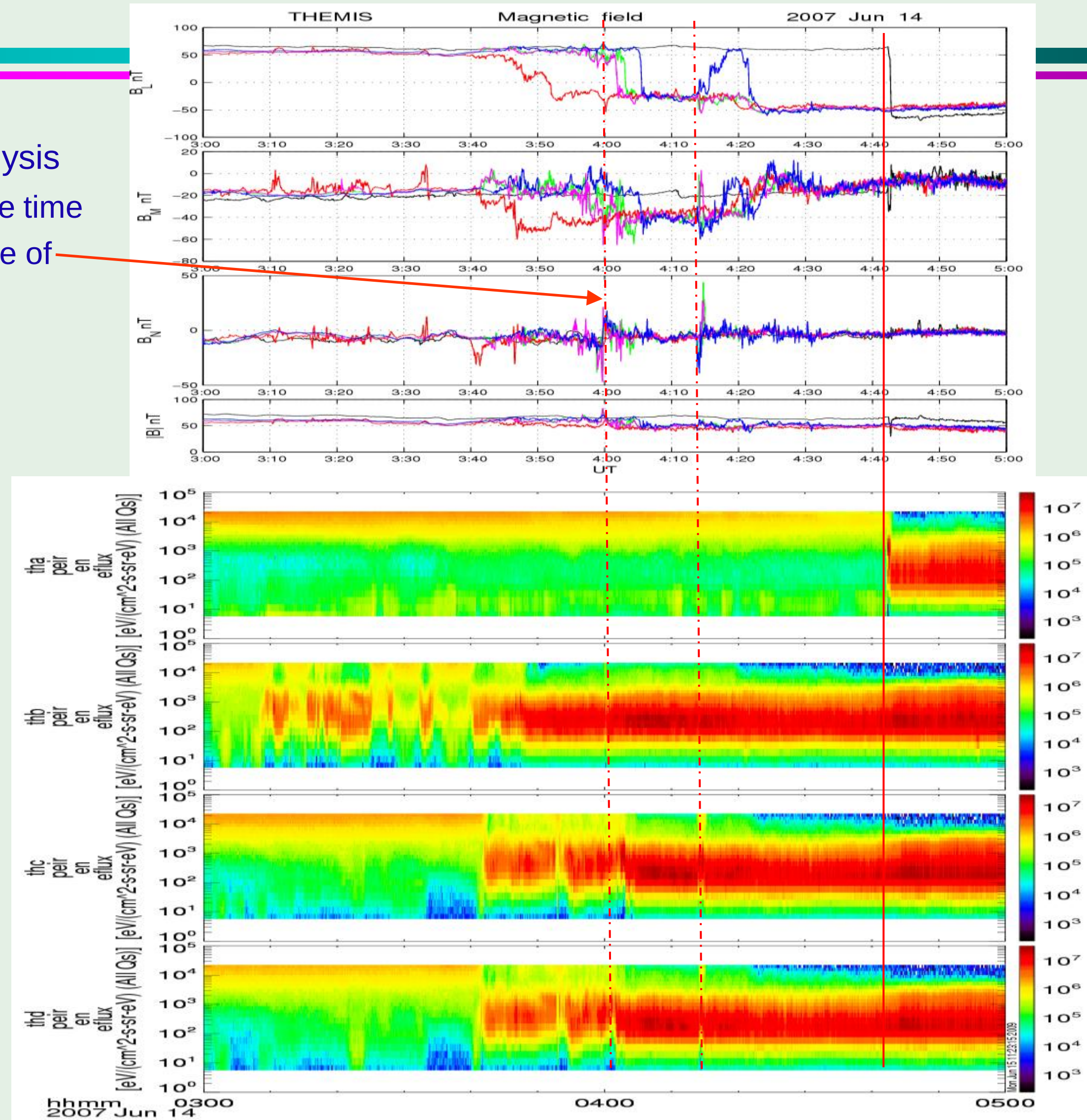
14 June: THEMIS configuration at earlier MP crossing

Cross MP one-by-one south of x-line; three typical FTEs observed.

Hasegawa et al. 2010

- B, C, D, & E in a tetrahedron configuration
- motion and orientation from 4-spacecraft analysis
- TH-A and TC-1 inside magnetosphere at the same time
- Plasma data show complex behaviour: suggestive of reforming, or double x-line.





14 June:

earlier MP crossing

Zhong et al. 2012

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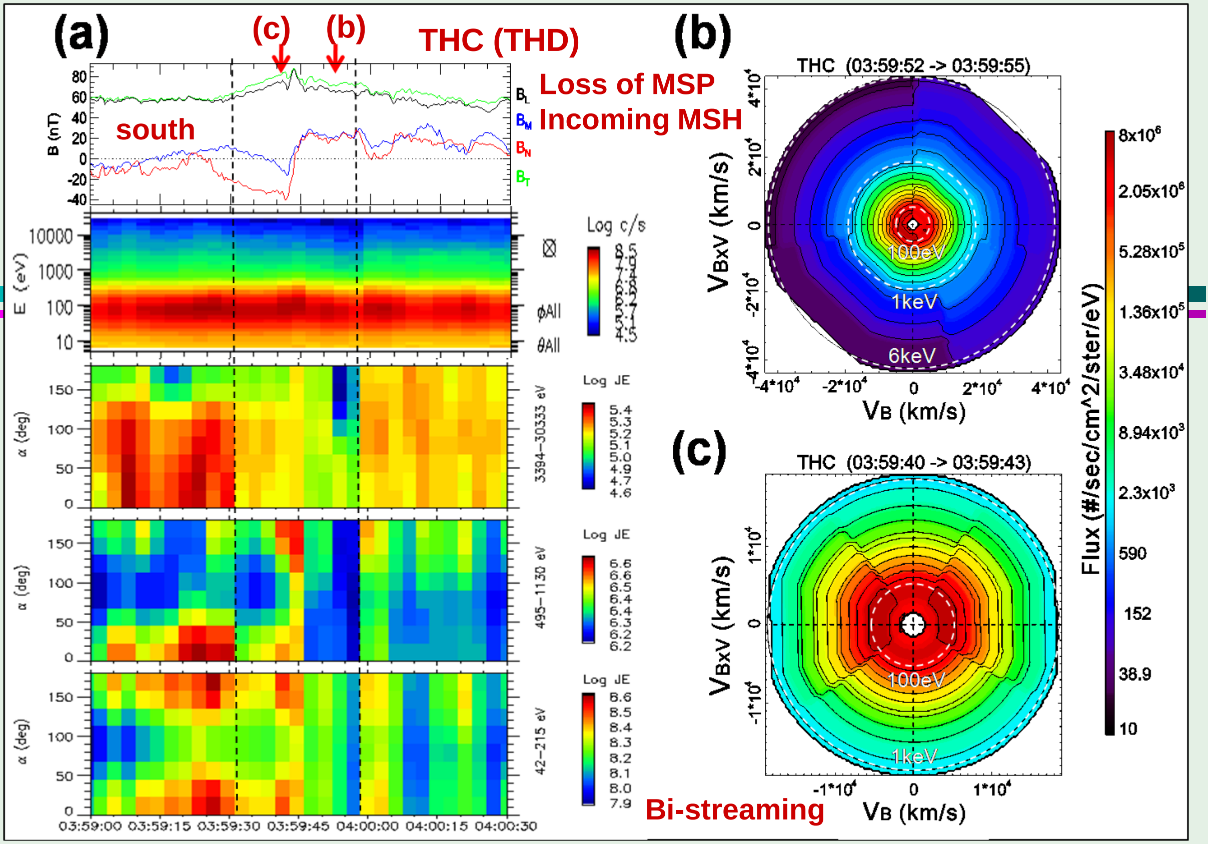
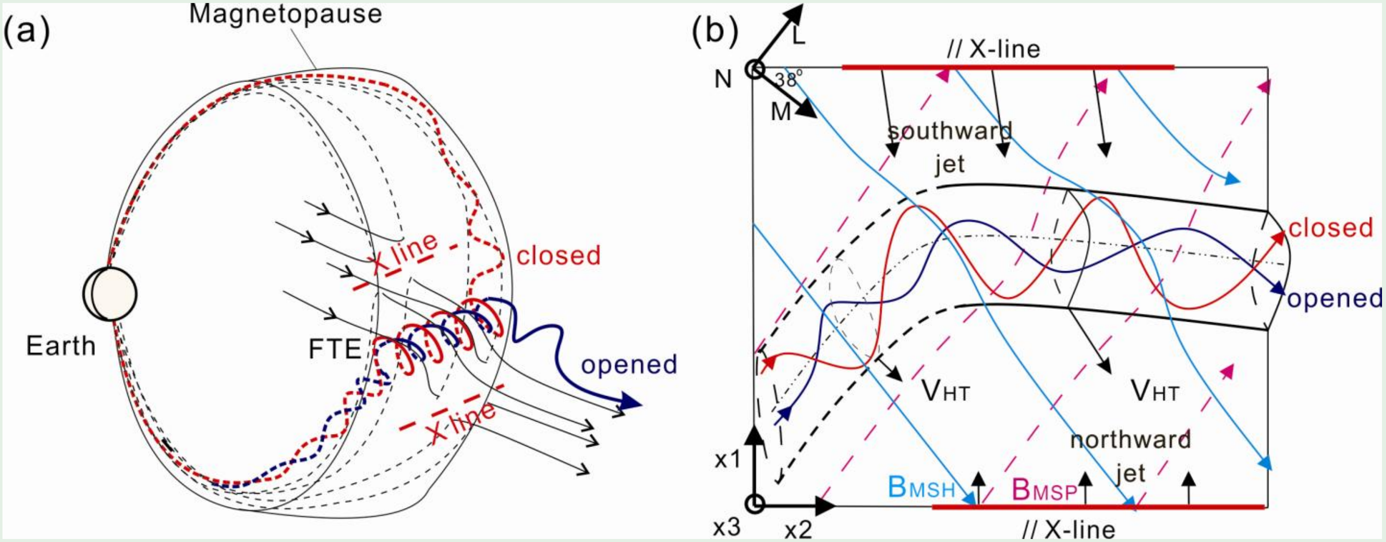


- Multi-spacecraft Themis coverage suggests the twisted 3-D geometry below
- Distinct orientations for m'spheric (THC/THD) and m'sheath (THB) branches of FT as shown.
- Plasma signatures show mixed open and closed distributions deep inside the FT.
- Signatures of recently closed LLBL seen on south side of FTE.
- Suggests SMXL formation



Conclusions: wide local time

Reconnection signatures tracked across a wide range of local times (10 spacecraft)

Cluster, Double Star & Themis sites provide details of FTE occurrence and motion:

Confirmation of east-west opposite moving FTEs

Consistent with a tilted, sub solar X-line (strong IMF By)

Generation far from local noon at local flank anti-|| sites.

Find simultaneous X-line structure at two locations along sub-solar merging line:

~9 Re separation.

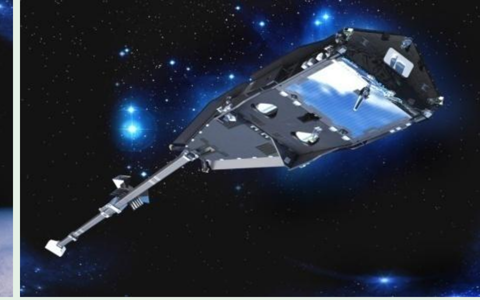
Suggests (patchy) reconnection occurs, irrespective of clock angle.

(all along the expected merging line)

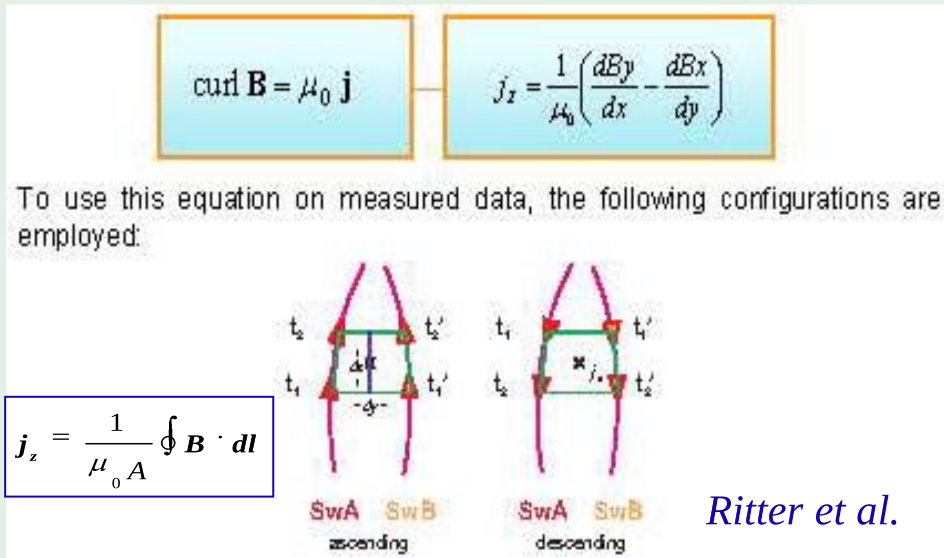
Evidence of SMXL formation using complex plasma and field structure seen with an FTE.

Surrounding incoming flows and 3-D geometry supports the interpretation

Swarm Concept:

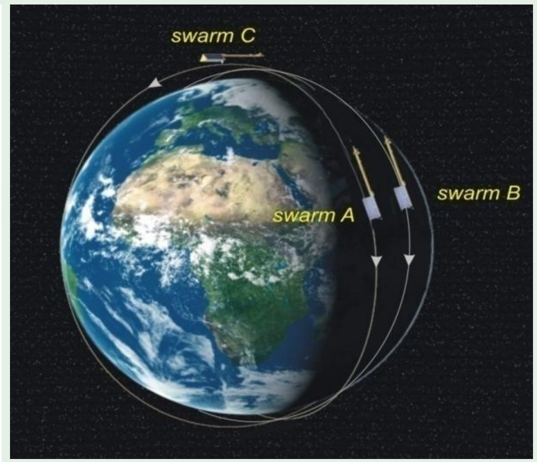


Calculation of FAC (strictly: vertical currents)
Direct modelling of equatorial induced field

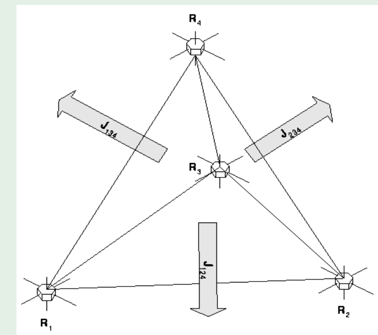


$$j_z = \frac{1}{\mu_0 A} \oint B \cdot dl$$

Ritter et al.



Lessons Learned From Cluster !!



One face:

$$(\nabla \times B)\cdot(r_{12} \times r_{13}) = \Delta B_{12}\cdot r_{13} - \Delta B_{13}\cdot r_{12}$$

Comparisons with less than 4-spacecraft:

- stationarity assumption
- single face: lack of knowledge of other j-components

  quality control difficult
- Enormous benefit from additional s/c:

  Cluster: desire 4 s/c, bunched

  Swarm: exploit initial period of close 3 s/c

  'C' above 'A-B' (common LT)

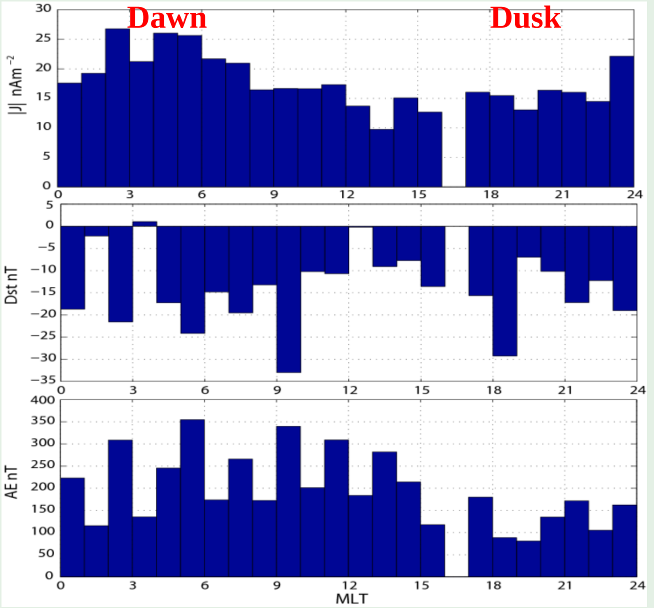
Spot comparisons with 4-spacecraft at MEO:

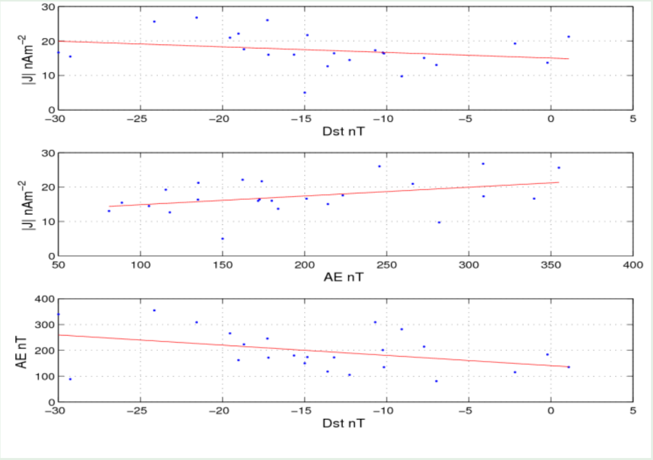
- Current components through each face: spacecraft configuration and scale are important.
- Local extent of FACs can be investigated in some detail using combination of boundary and curlometer analysis.
- Best estimates of particular components of curl B ($J\phi$ and J||) depend on sampling (orientation to RC).

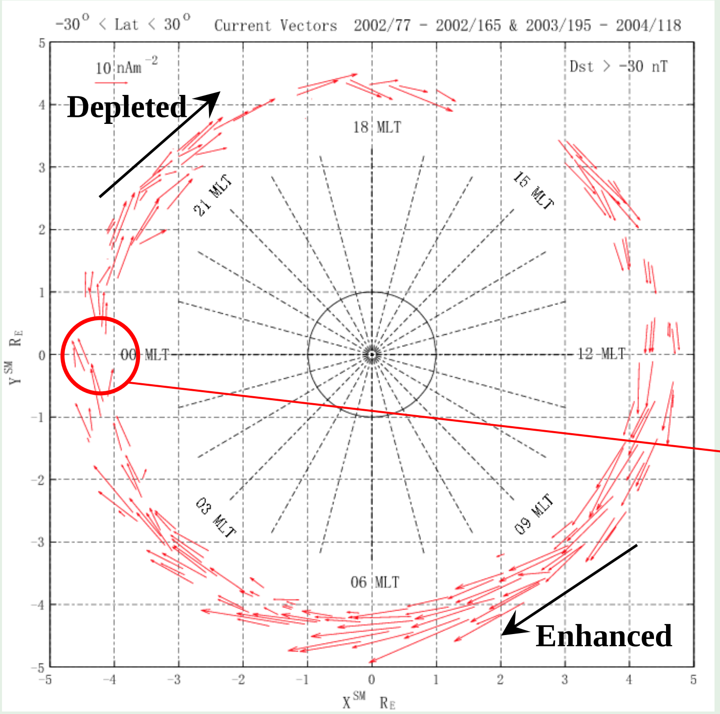
Ring current analysis: first, full azimuth scan of westward flowing RC

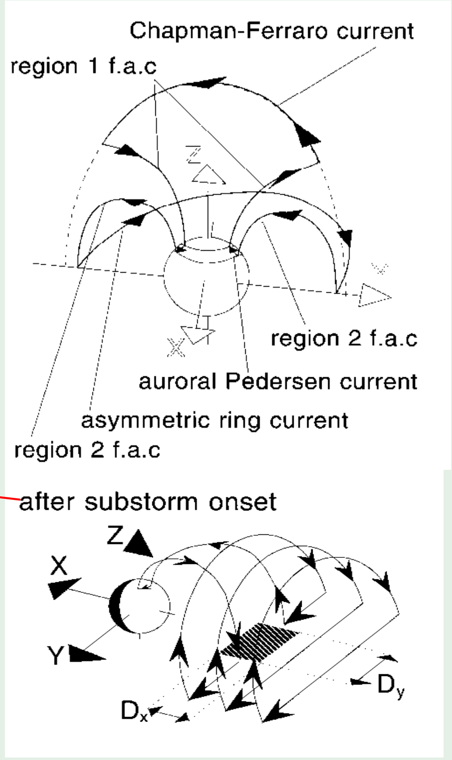
- The Cluster array often samples a well defined RC plasma signature during each perigee pass
- Adaptation of curlometer for azimuth (J_φ) and parallel ($J_{||}$) components.
- New field curvature and rotation analysis may provide enhanced results [*Shen et al. 2012*]

- RC grows away from noon on dawn side (fed by upward R2 FACs)
- RC decays on duskside towards noon (feeds downward R2 FACs)
- Minimum near midnight: possible inner edge SCW DP1current [*McPherron, 1973*]
- Correlations with AE and Dst show that seasonal and dynamic variations do not account for the dawn-dusk asymmetry.





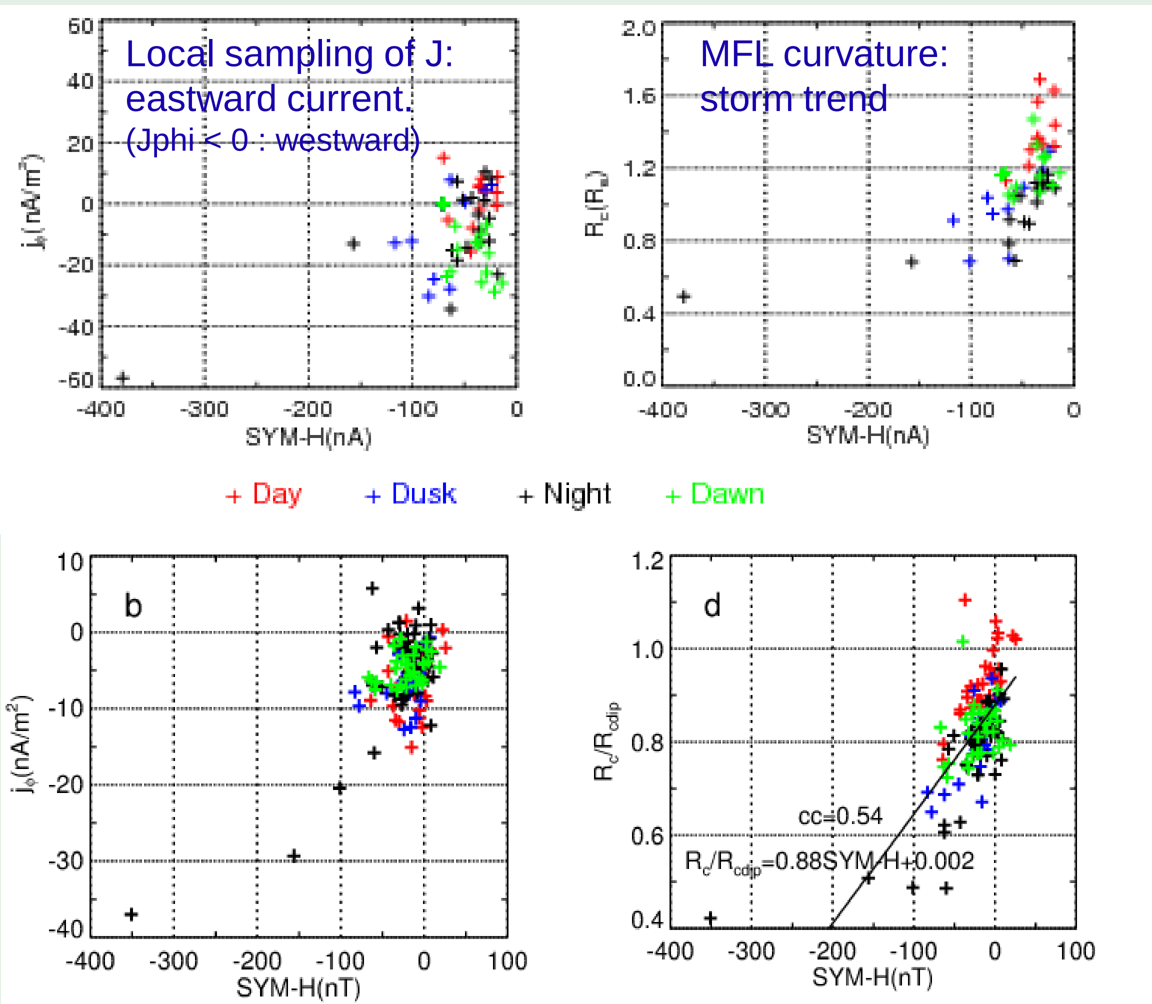


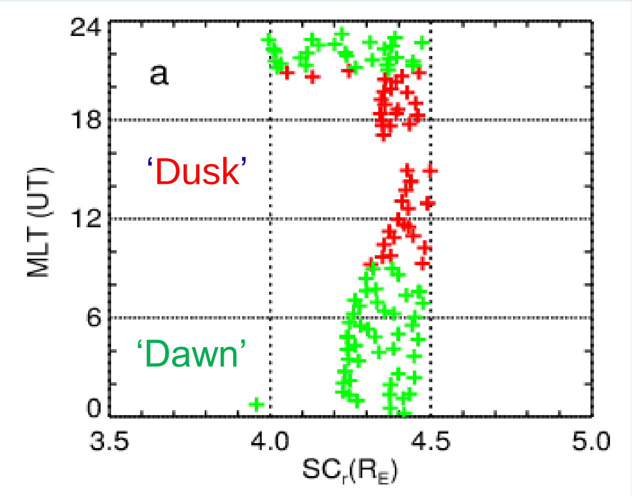


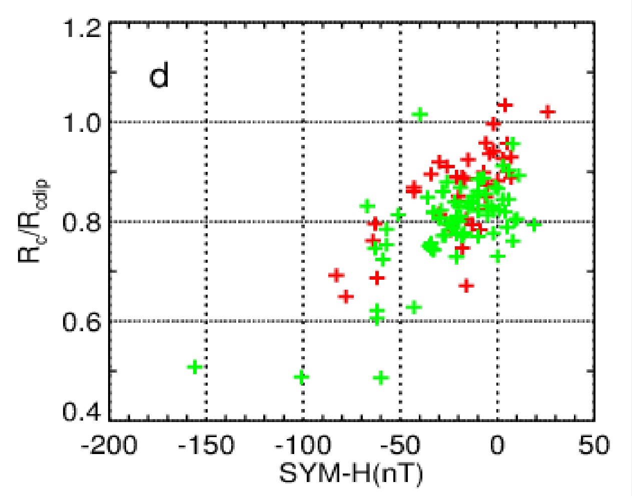
Ring current analysis: statistical trends

Below: combined statistics for current density and field curvature estimates.

Dawn-dusk bias reflected in field curvature estimates.







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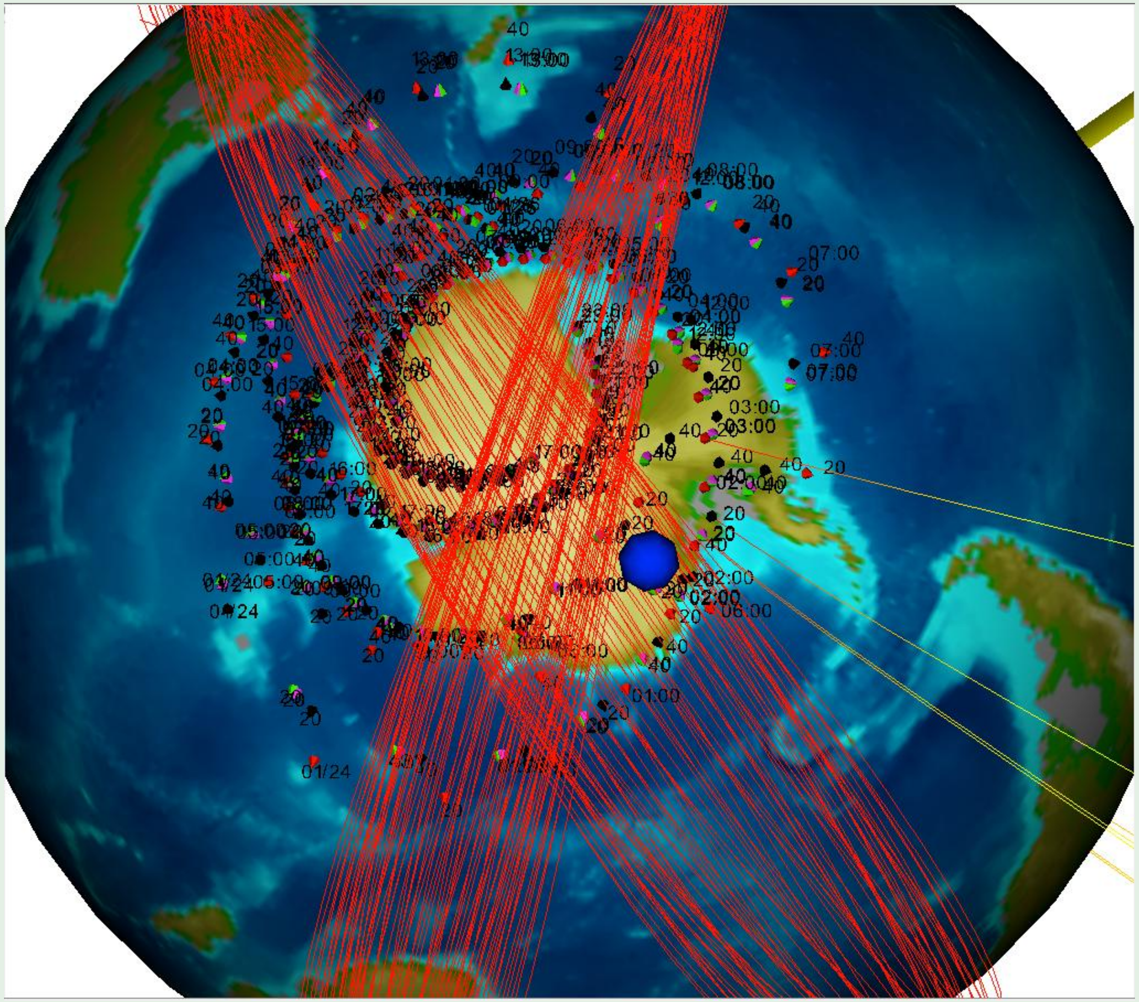
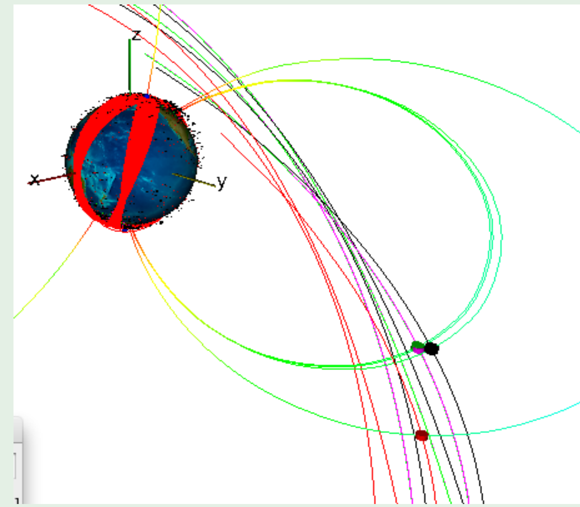
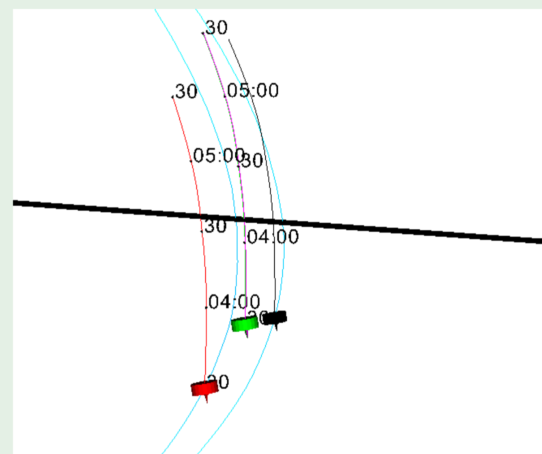
Swarm-Cluster coordination:

High latitude FAC conjunctions; low latitude RC signals mapped every orbit.



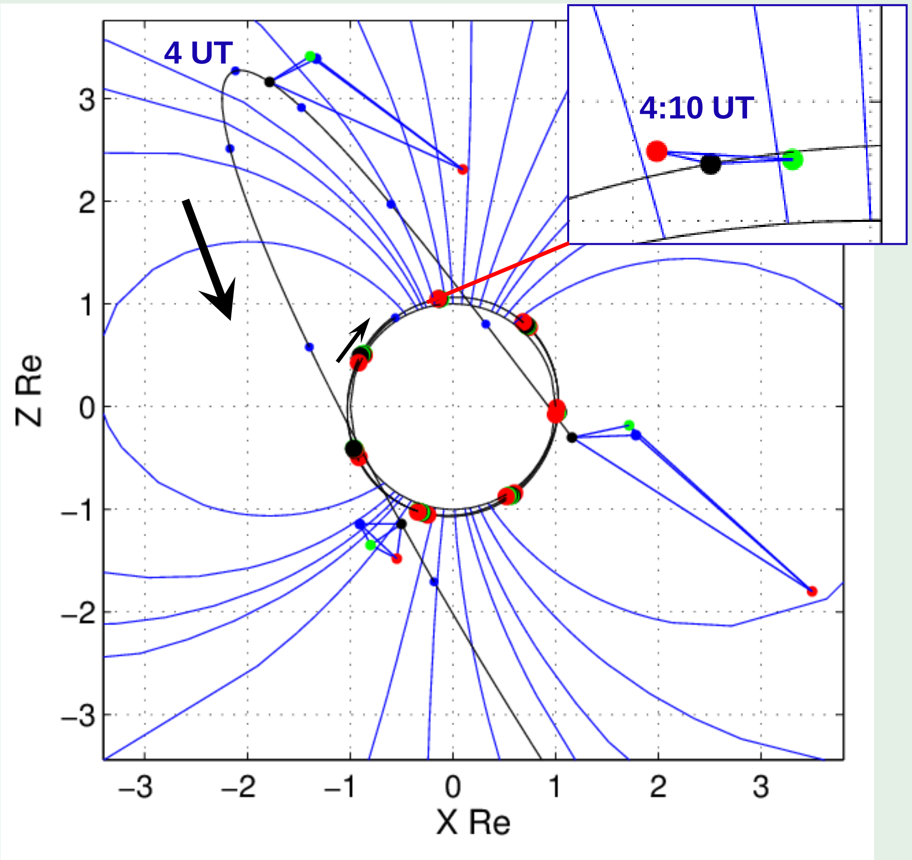


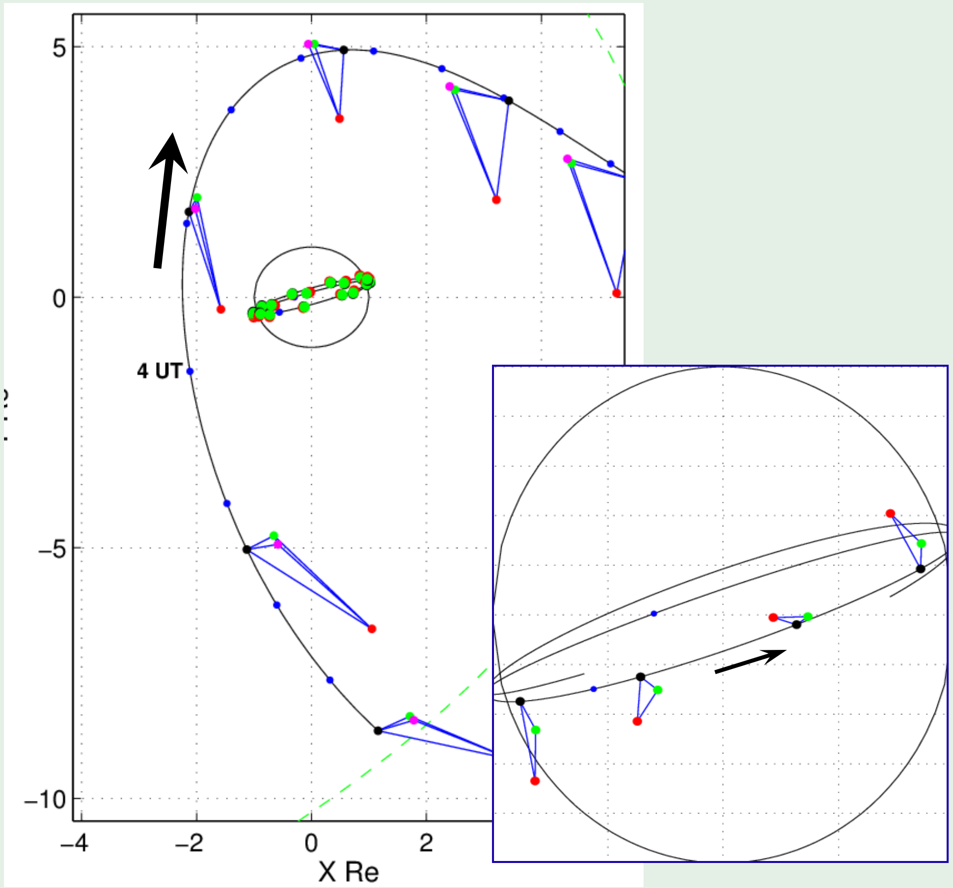


SM equator crossing: SC2 behind by 30 mins - adjusted.

Cluster-Swarm Key configurations: 2014

Initial Cluster configuration set for the ring current: to access curl(B).
Orbit tilt samples range of LT giving good local coordination between Cluster and Swarm.

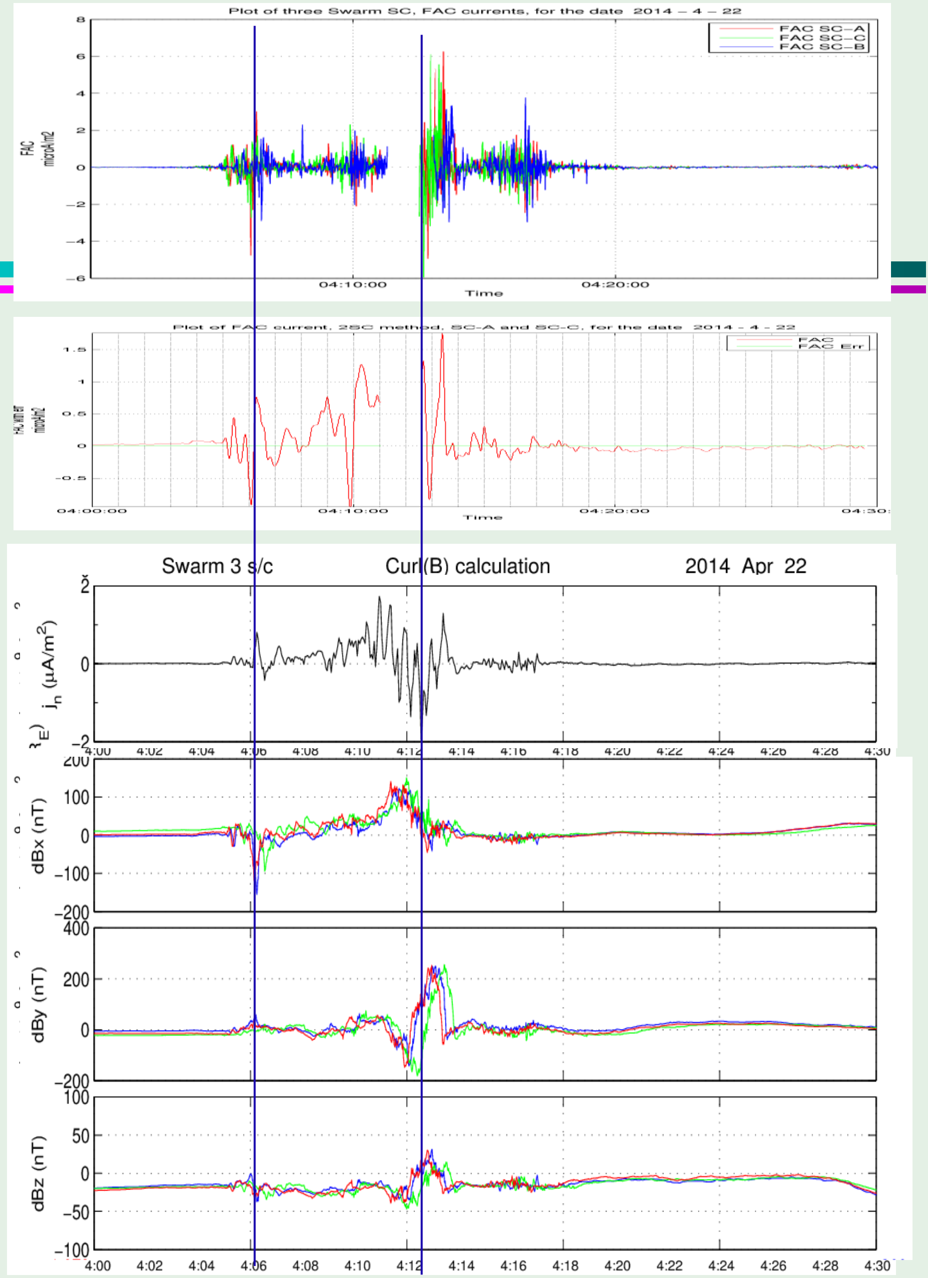


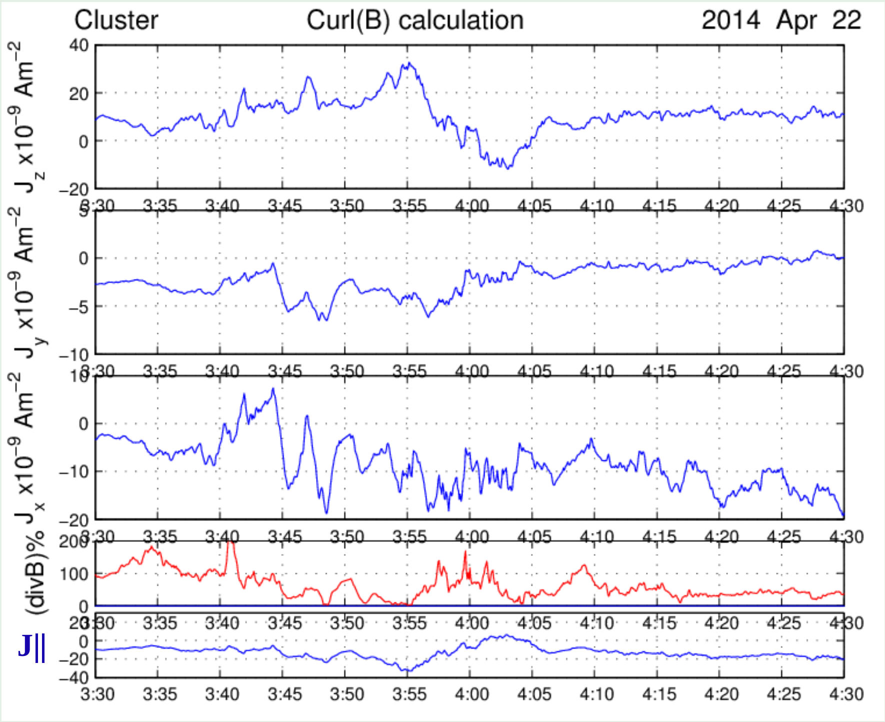


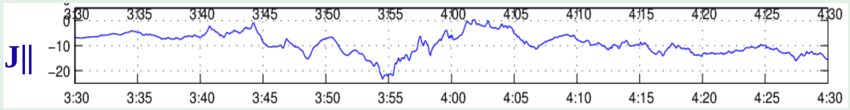
Example 2, 2014 April 22: shows close LT alignment with Swarm during Cluster FACs (4:00-4:15 UT).
Inset shows close grouping of 3 Swarm spacecraft. (A, B, C = black, red, green)

Comparison of FAC estimates: detail

Curlometer at cluster compared to 3 s/c
FA component for two s/c planes: persistent signature







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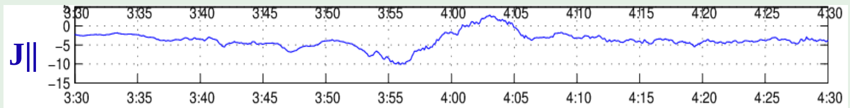
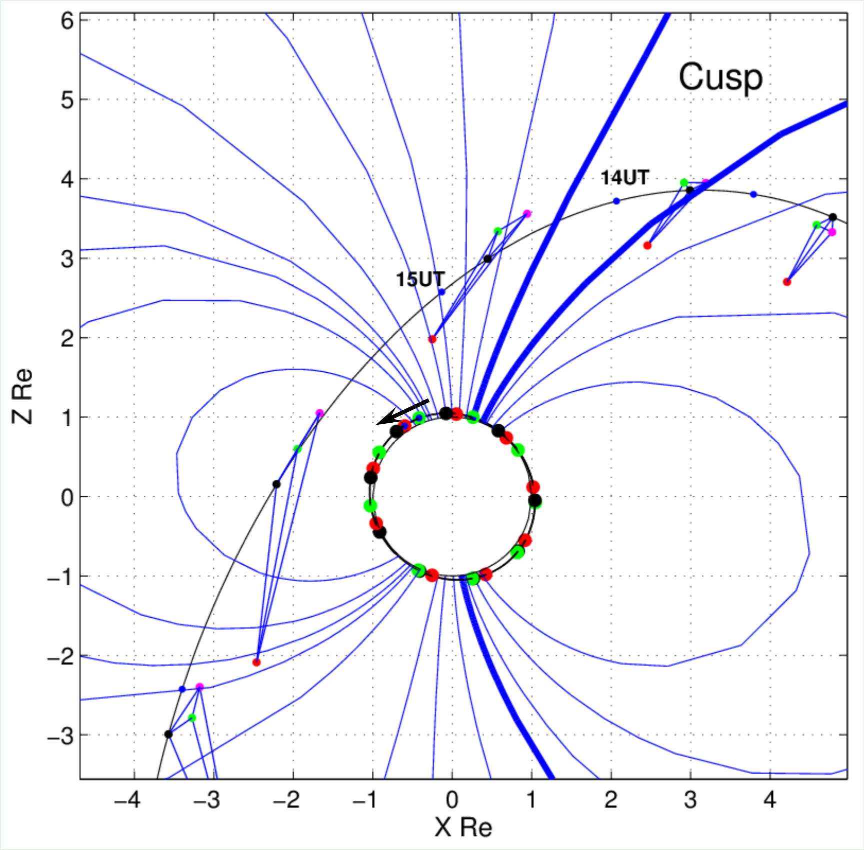


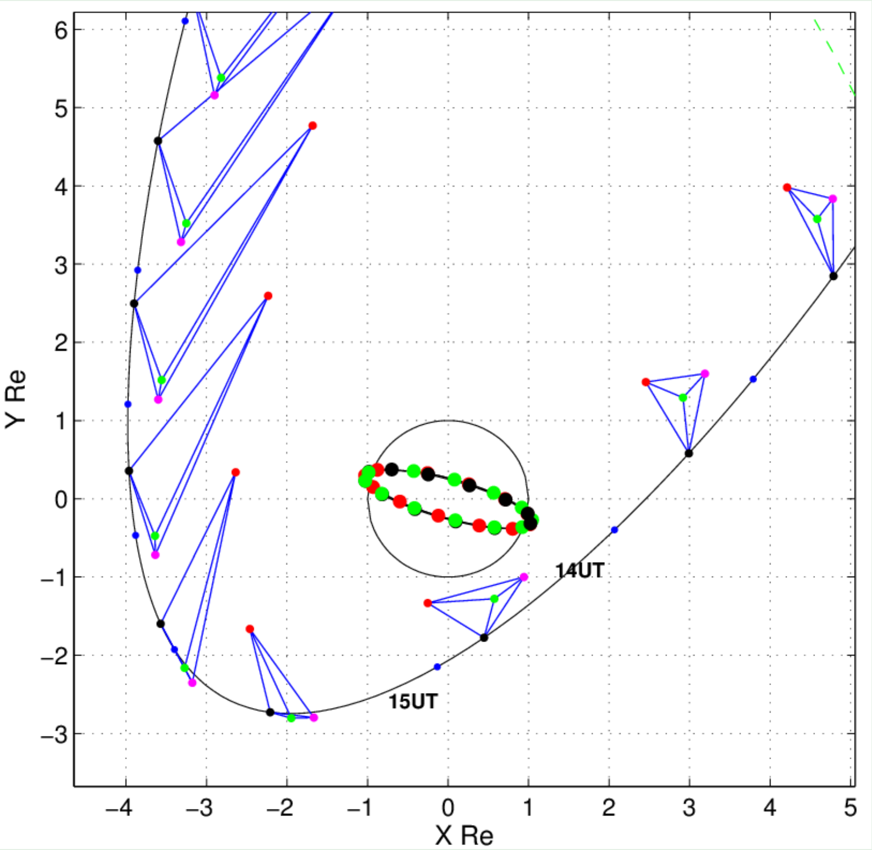
1,2,3

Example, 2014 April 22: Comparison to Curlometer 3 s/c estimate.
1st period well correlated to 2 s/c Swarm method.

Cluster-Swarm Key configurations: cusp

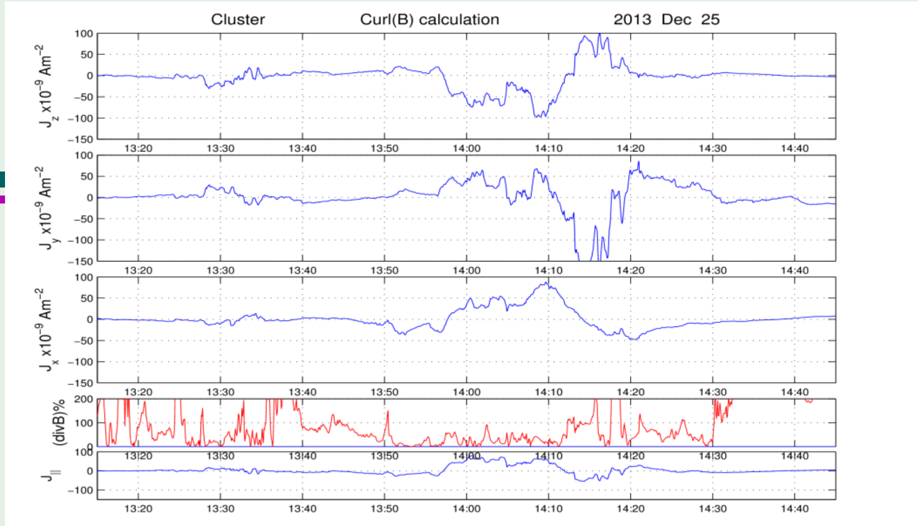
Second target for cusp encounter is more rarely encountered through the tilt in the cluster orbits, but achieves close configurations on the same orbits as the RC crossings.

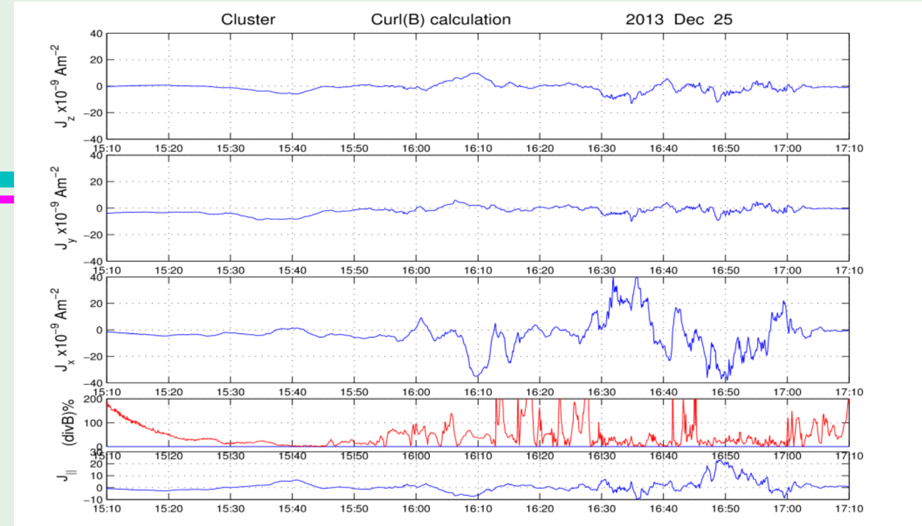


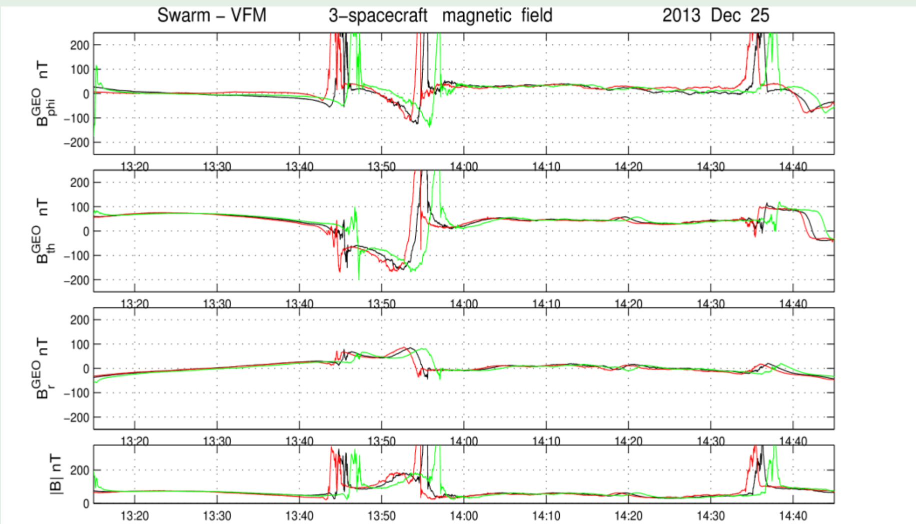


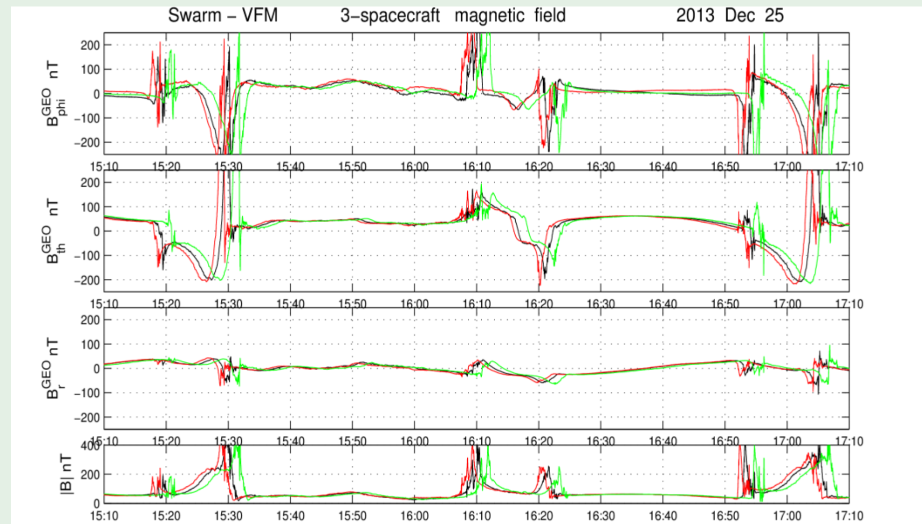
2013 Dec 25: Cluster passes through cusp 13:30-14:30 UT; then through the FAC +(inner)RC 15:30-17 UT. Good LT alignment with Swarm at Cusp crossing.

Cluster-Swarm Key configurations:



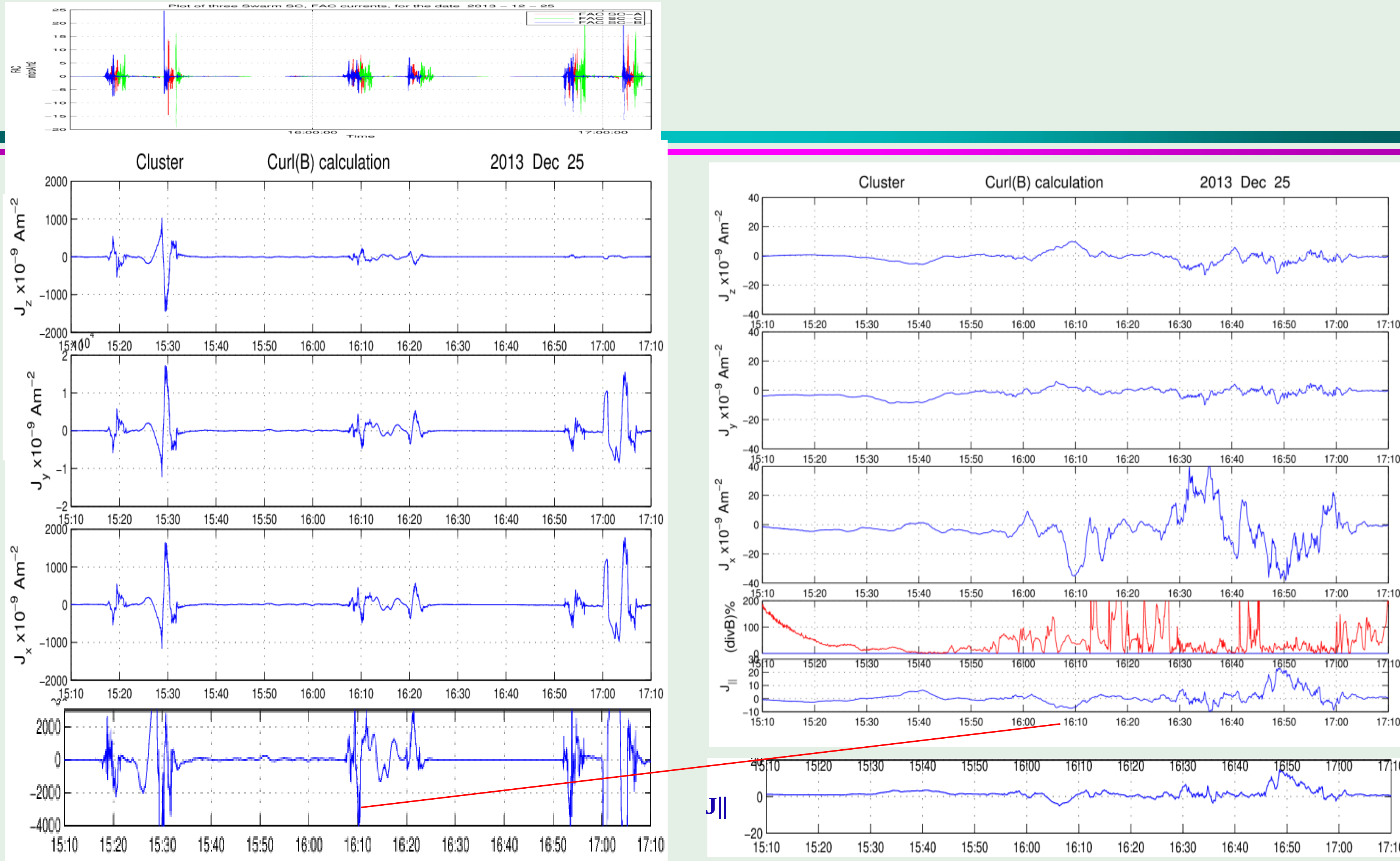






2013 Dec 25: Comparison with Swarm residual data (subtraction of Chaos-4 plus model).
Cluster passes through Cusp just after high latitude passage of Swarm.
Cluster enters FACs as Swarm reaches high latitude.
Cluster FAC signature is consistent with R2 connectivity (+/- 20 nAm^{-2}).

Cluster-Swarm Key configurations:



2013 Dec 25: Cluster enters FACs as Swarm reaches high latitude.
Matched FAC signature at Cluster and Swarm.

Science & Technology Facilities Council

Conclusions: Swarm-Cluster

Adaption of Curlometer to both Cluster perigee and Swarm LEO.

The adaption of advanced Cluster tools with < 4 spacecraft.

Application to 2 and 3 s/c Swarm data interpretation

Swarm-Cluster coordination:

Test connection through R2 FAC: clarification using the Swarm polar coverage.

Opportunities for both direct conjunctions and statistical comparisons with Cluster.

Tests of various techniques using both Cluster and Swarm:

Alternative techniques tested for multi-spacecraft analysis and

Magnetic gradient estimates: identify quality indicators

Comparative measurements from Cluster provide spot checks of, e.g., RC or FAC signals

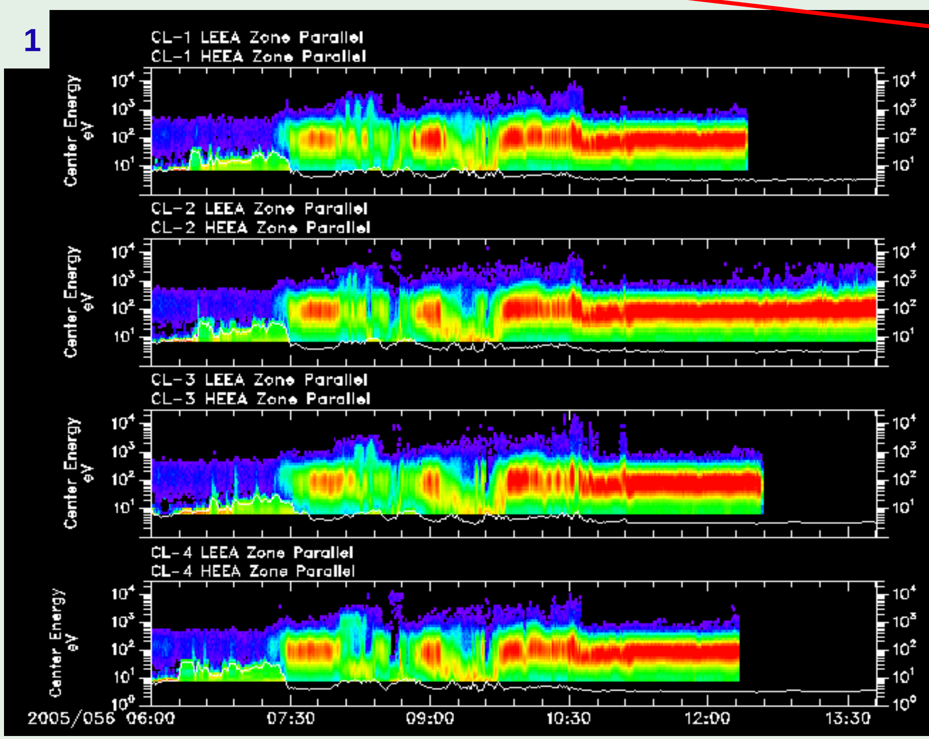
Cluster-Double Star conjunction: Onset of high latitude MR?

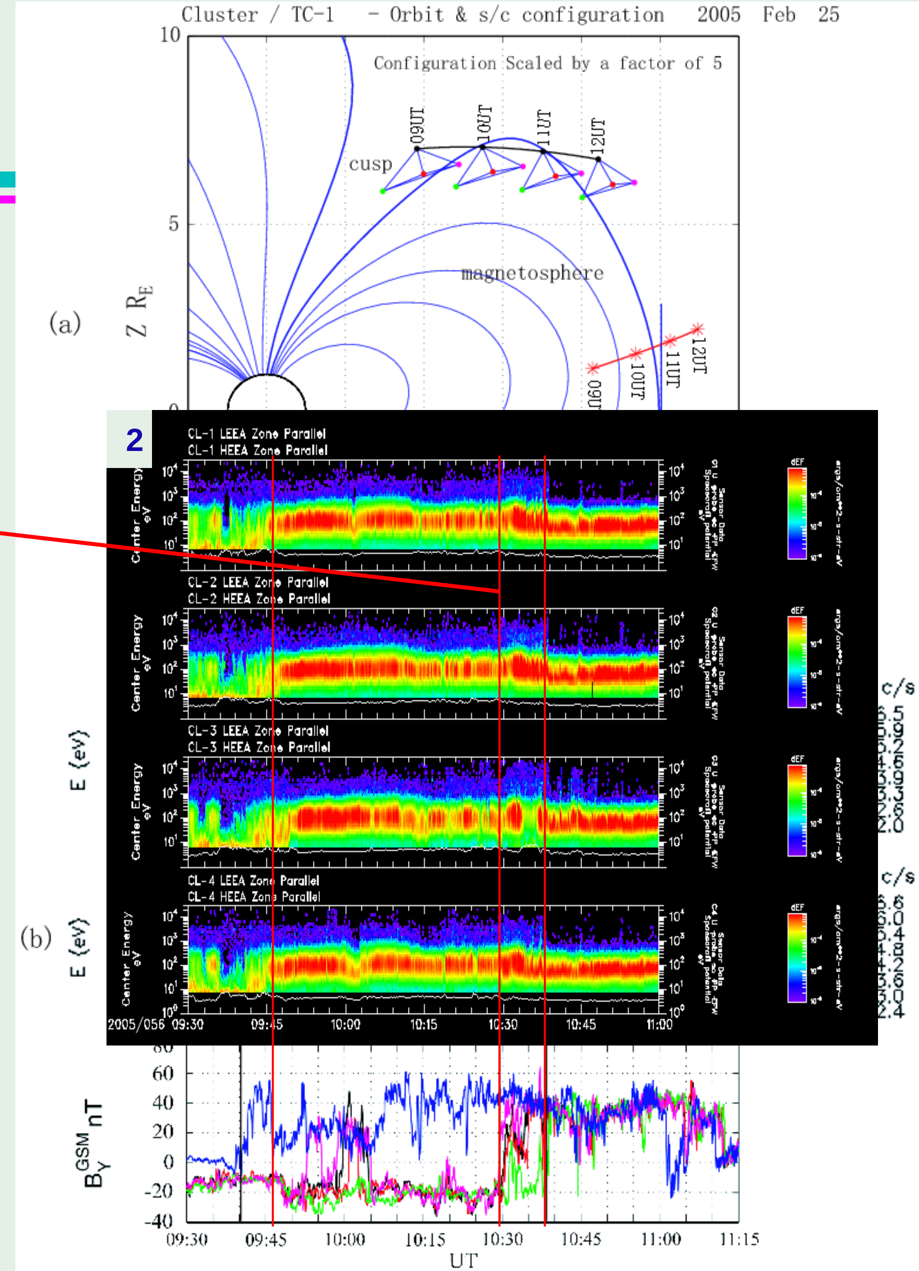
Cluster electron data shows: correlated, energised field aligned signatures.

1. Cluster moves from the polar cap via dynamic cusp to the M'sheath at slow crossing ~10:30 UT: accelerated electrons.

2. Cusp/BL signatures populated by open field lines, detailed structure with mixture of M'sheath and M'spheric populations.

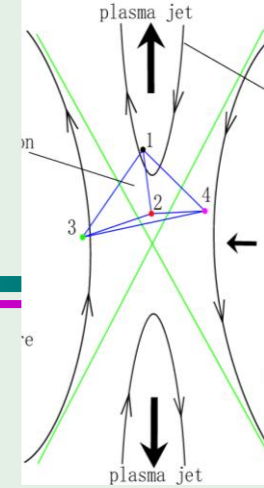
Observations are similar until final slow crossing: e.g. C3 detects low density region.

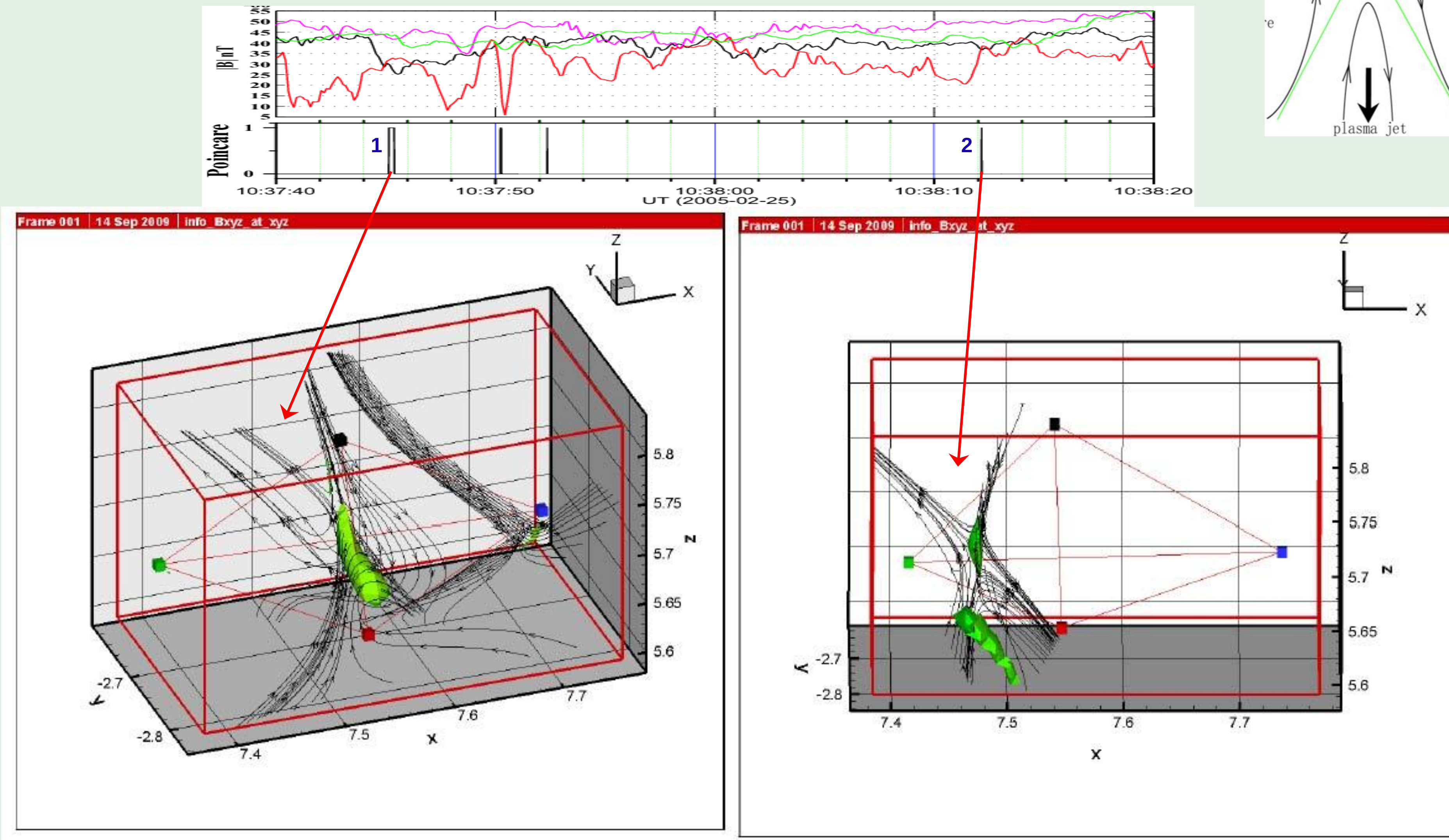




Sensitivity of X-line structure: reconstruction

1. Field lines at 10:37:45 UT. An A-type null appears on the near right of C2.
2. Field lines at 10:38:12 UT. Part of an A-null appears on the left of C2. A complete B-null is located at a larger y-position relative to the A-null.

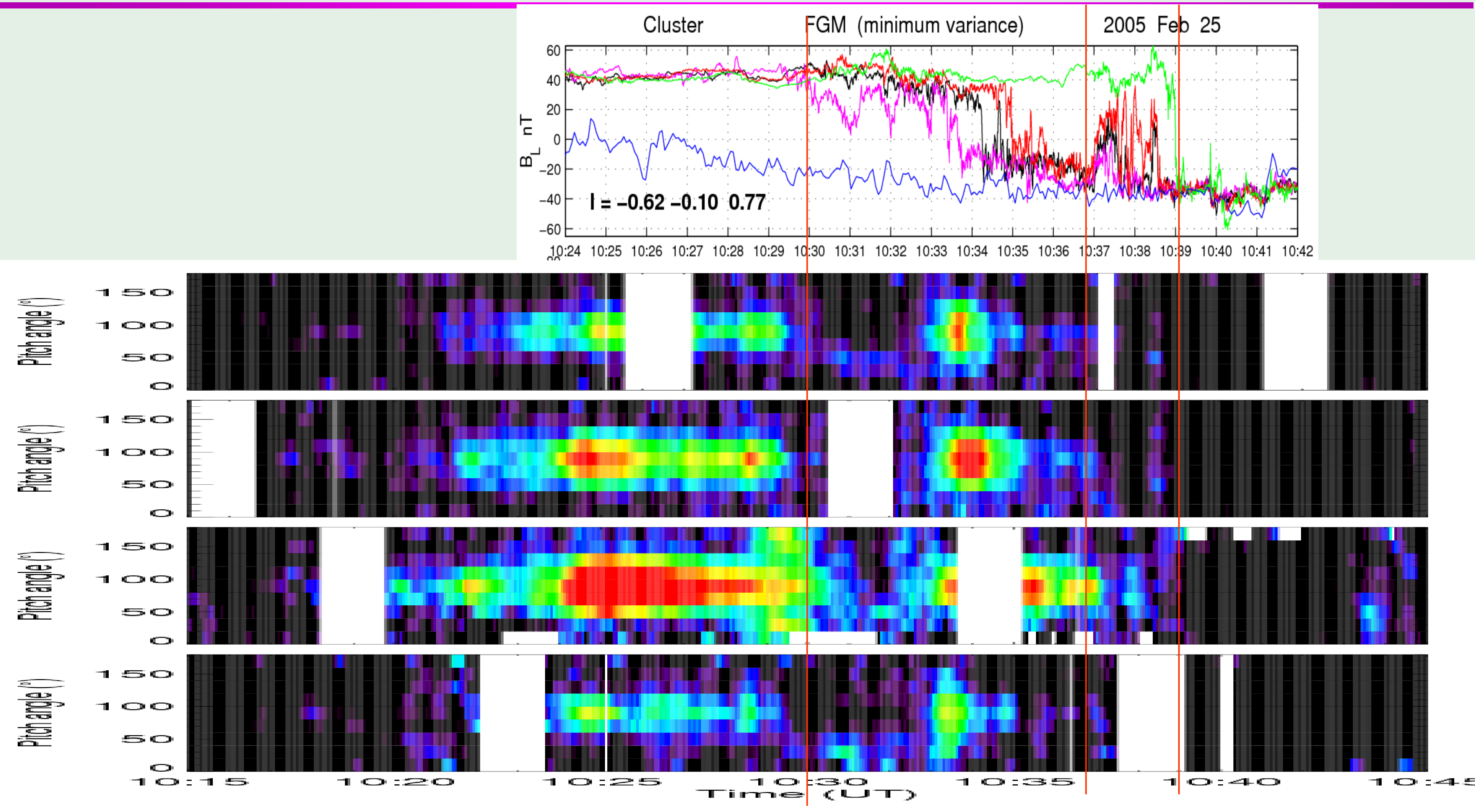




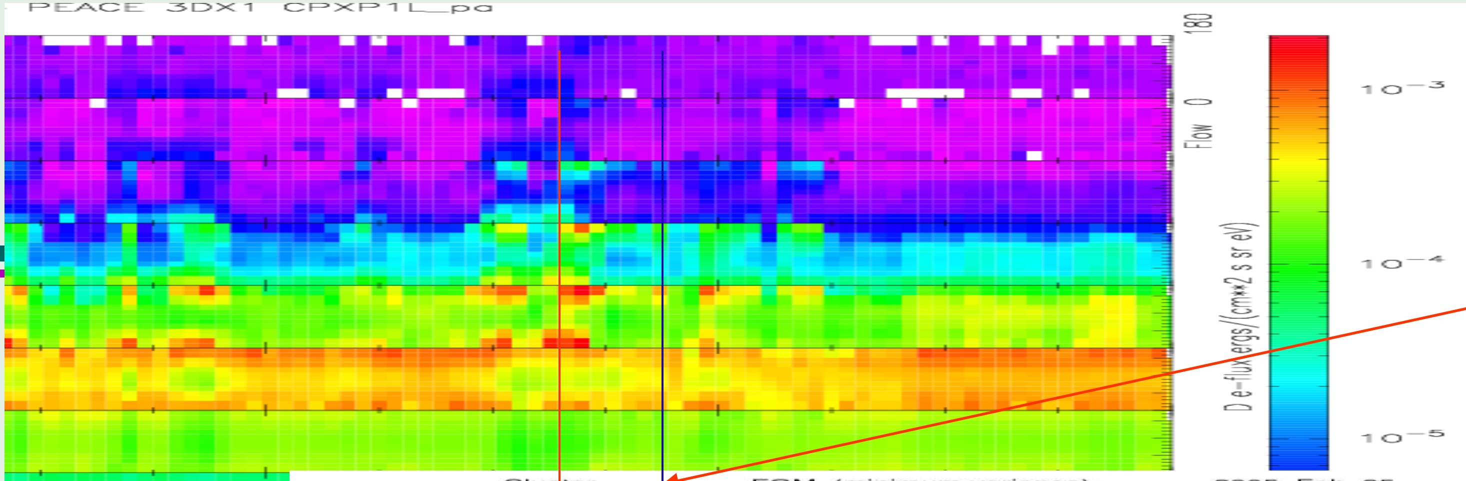
Electron data: 25 Feb 2005

Shows complex FA and trapped populations consistent with diffusion region encounter

Details TBD and need to clarify ion flows.

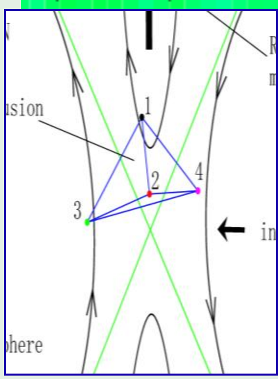


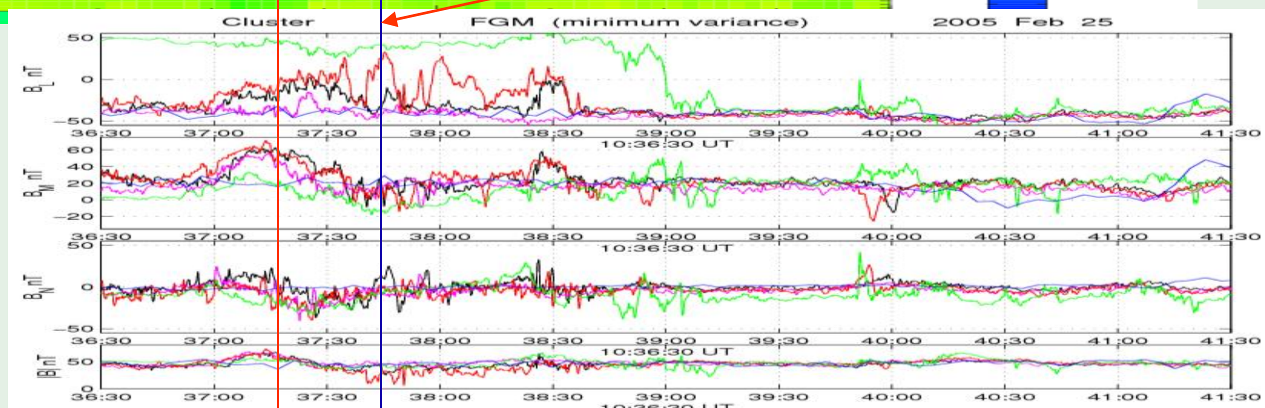
Ion & electron data: Cluster 4



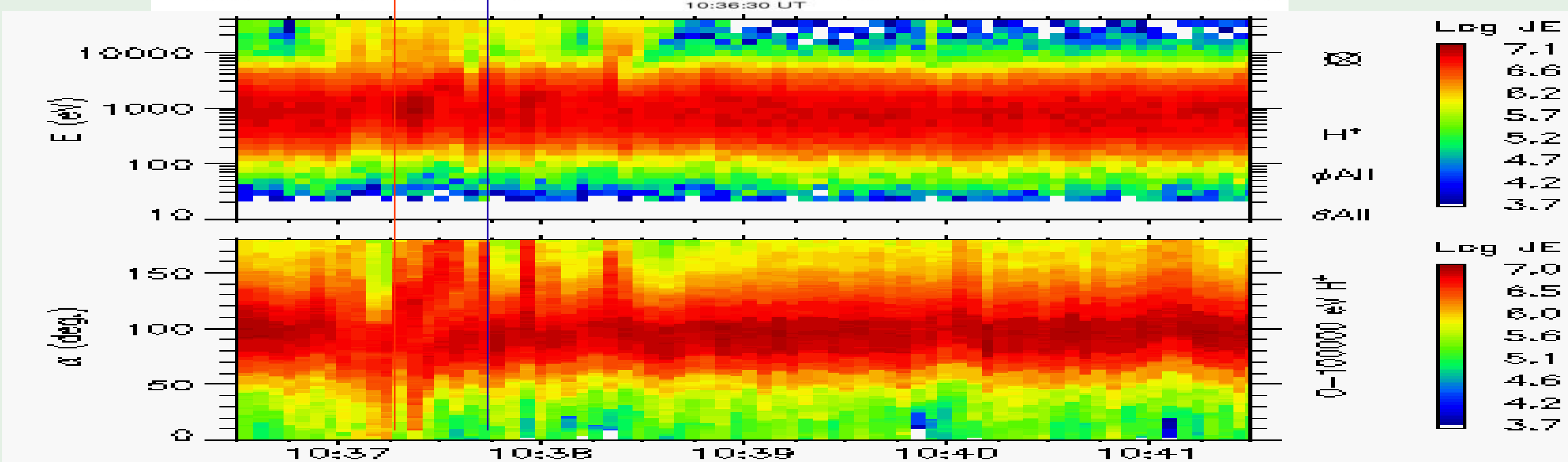
@ Null field: C4 in magnetosheath BL?

(inflow region)

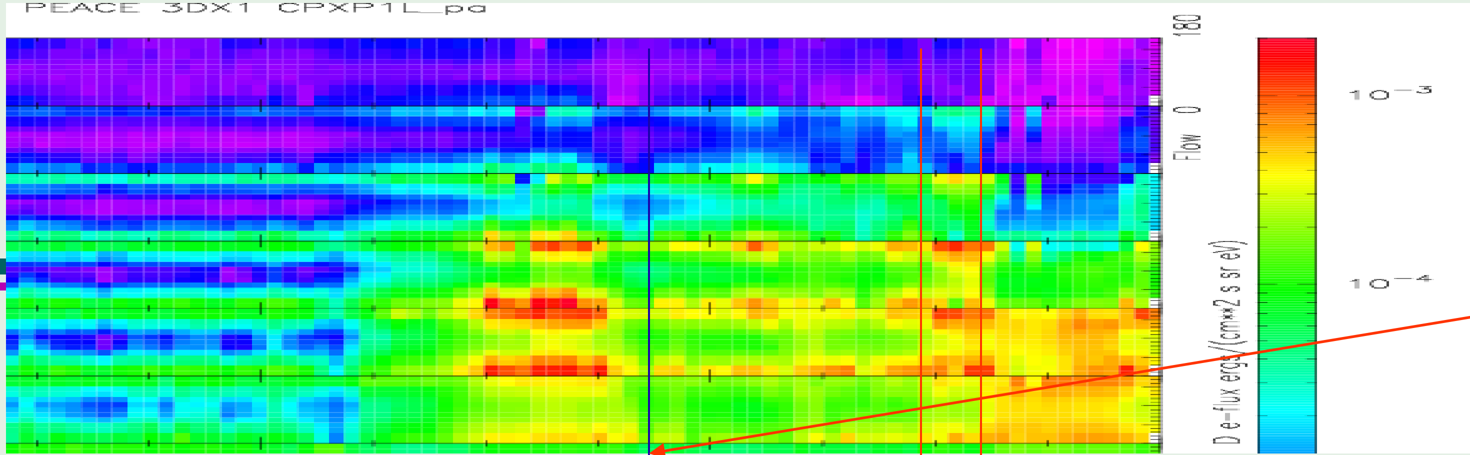




Broad ion distribution, centred on 90 deg PA.

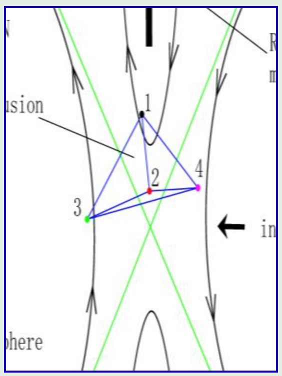


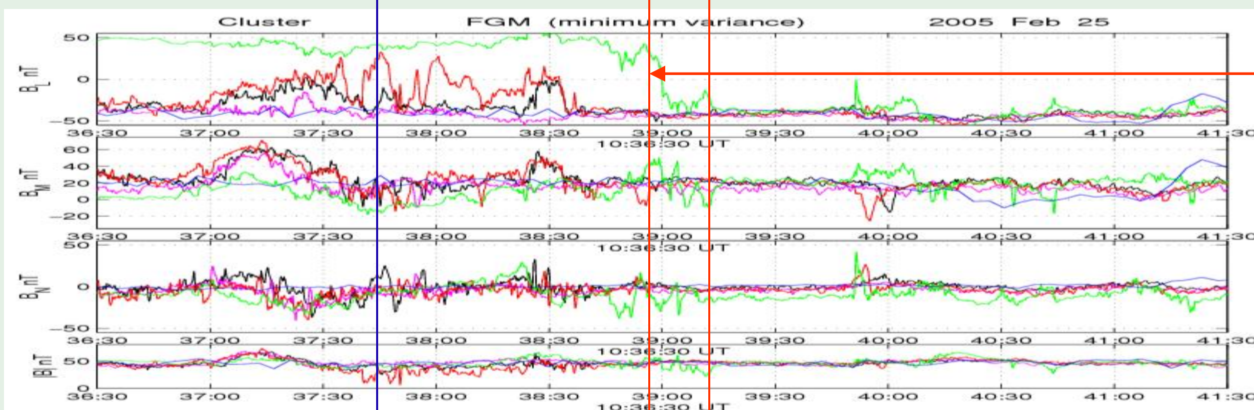
Ion & electron data: Cluster 3



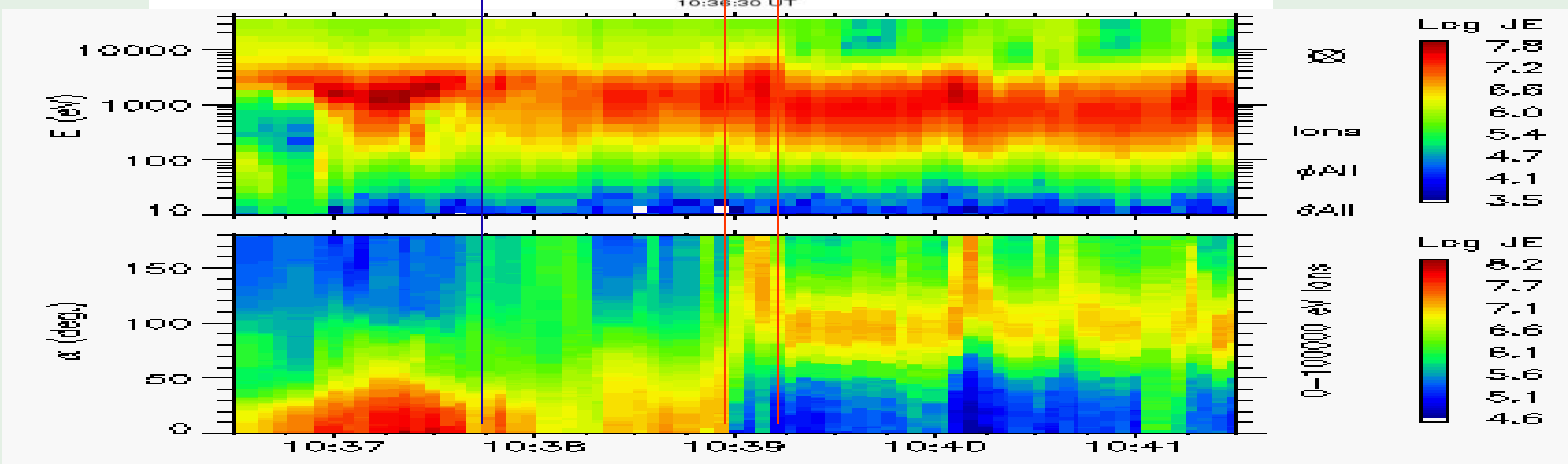
@ Null field: C3 in magnetospheric BL?

(outflow region)

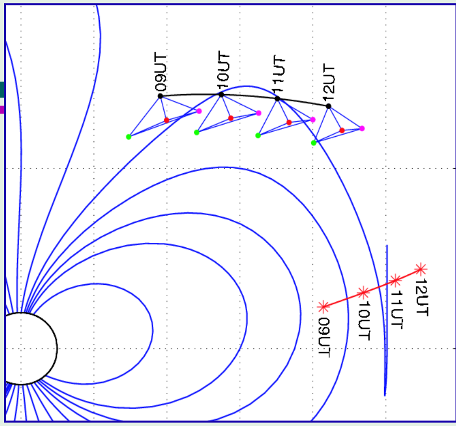




Ion beams suggest that C3 moves from south to north of the X-line.

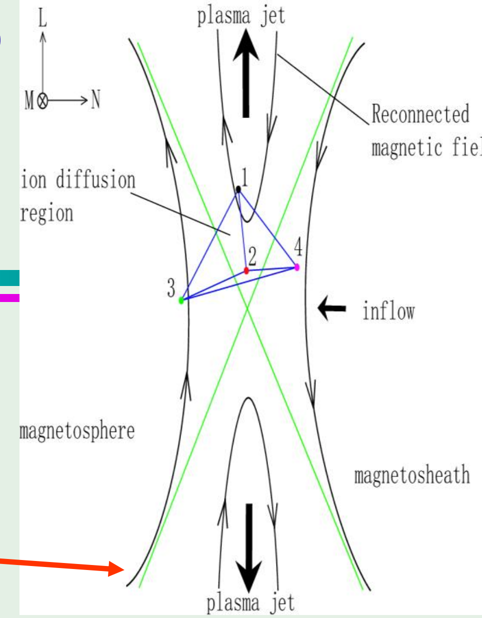


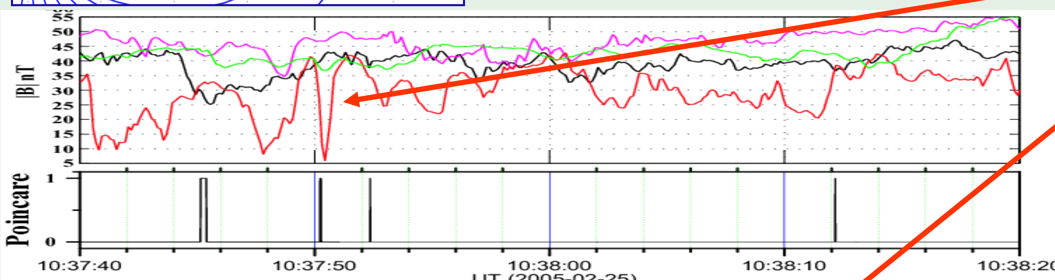
Direct sampling of X-line: Cluster scale ~1500 km, ion inertial scale ~70 km; BL ~2000 km. Single scale at Cluster suggests a persistent structure, with small relative motion taking the spacecraft in and out of the region. Electron distributions (not shown) correlated, energised field aligned signatures.

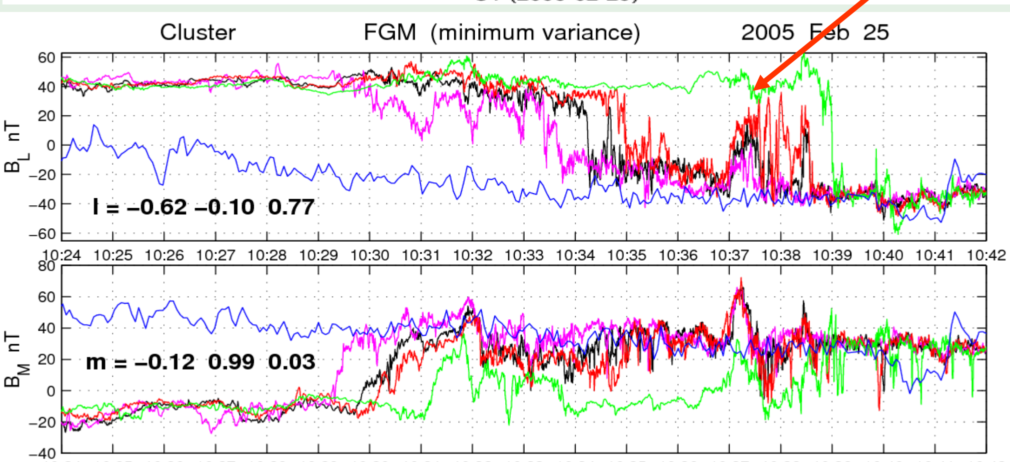


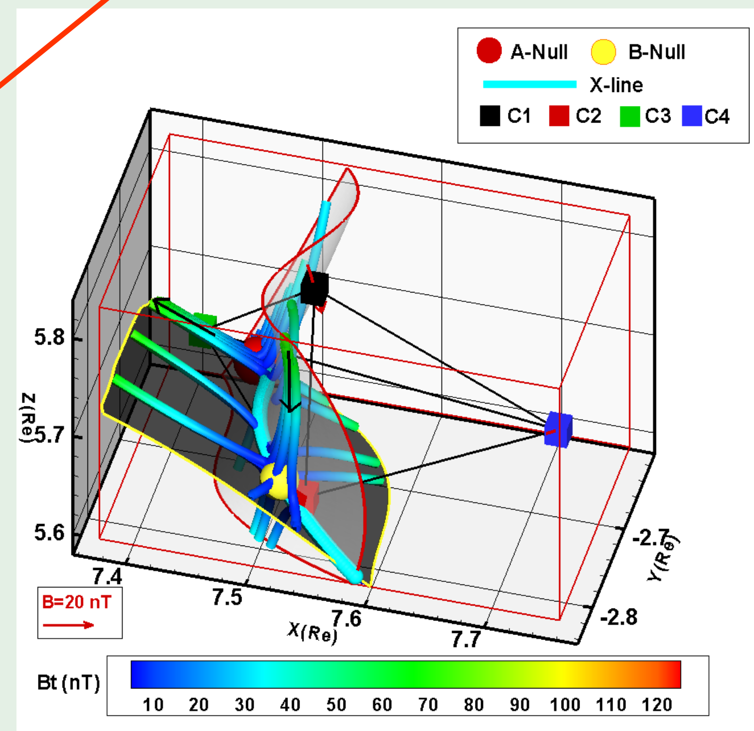
Follows period of low latitude reconnection at TC-1: C1, C2 see reversals of BL By consistent with Hall currents. Also consistent with anti-parallel reconnection site.

Poincare index shows existence of magnetic type A nulls and field reconstruction shows A-B null pair









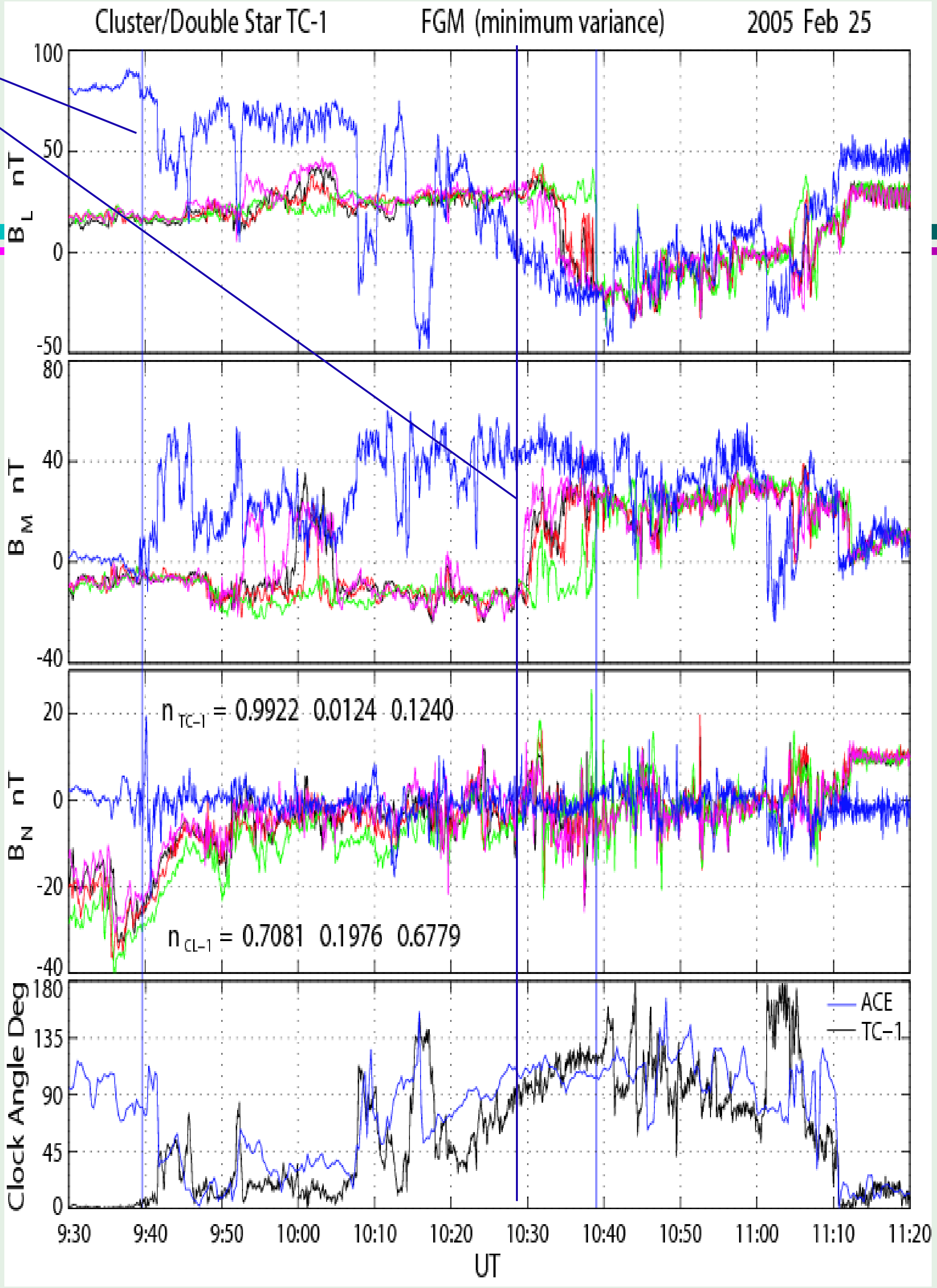
TC1 exit during normal low latitude merging

Standard FTE polarity at TC1 MP

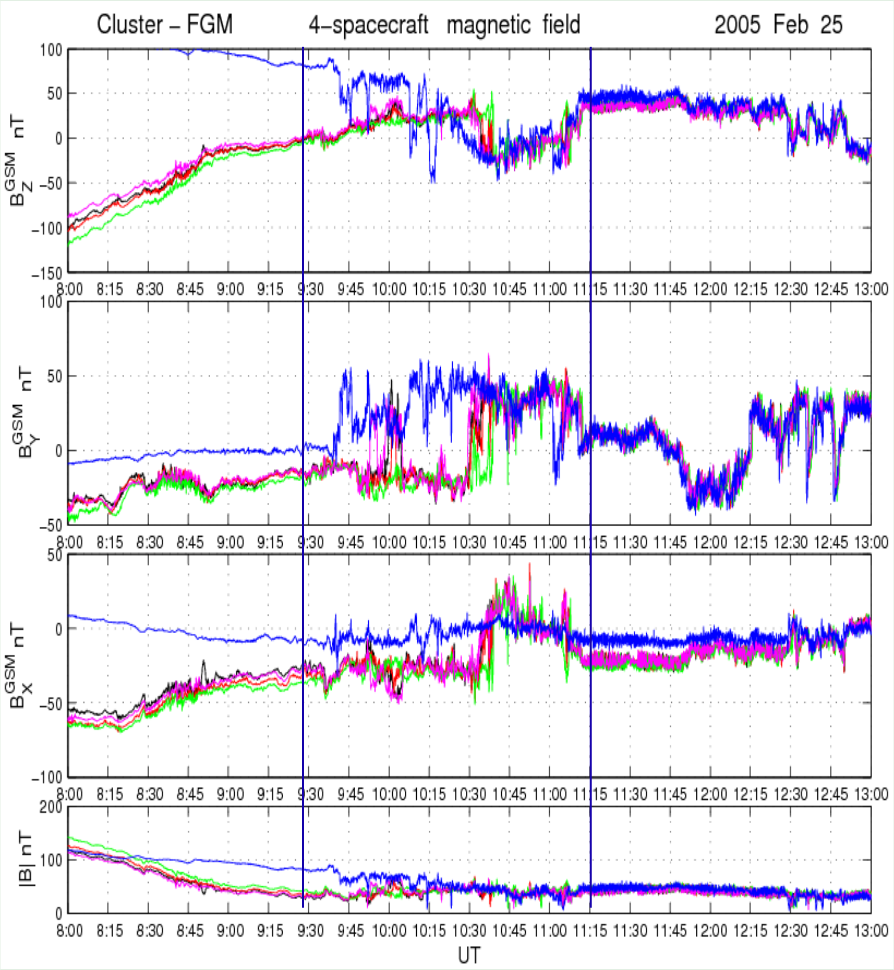
Later slow BL exit at Cluster MP (1-2 km/s)

All Cluster FTEs are northward moving (eastward component)

Polarity on Cluster and TC1 unclear after 10:30 UT



TC1 monitors magnetosheath during cluster exits

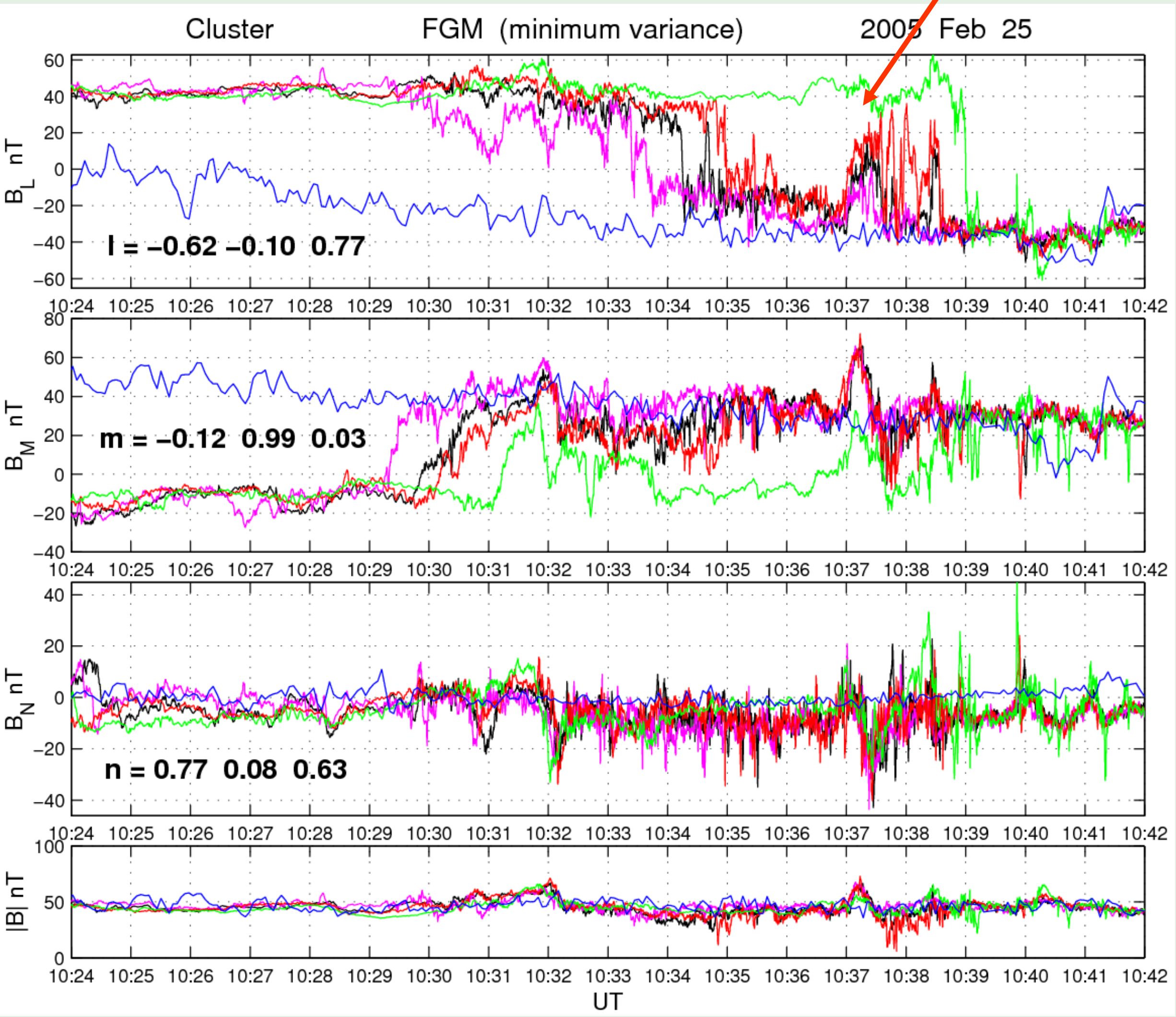


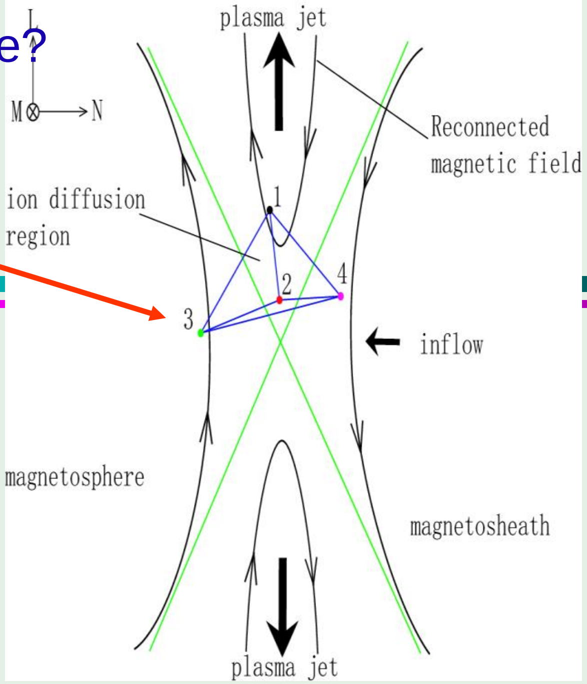
Magnetosheath crossing: Cluster direct sampling of X-line?

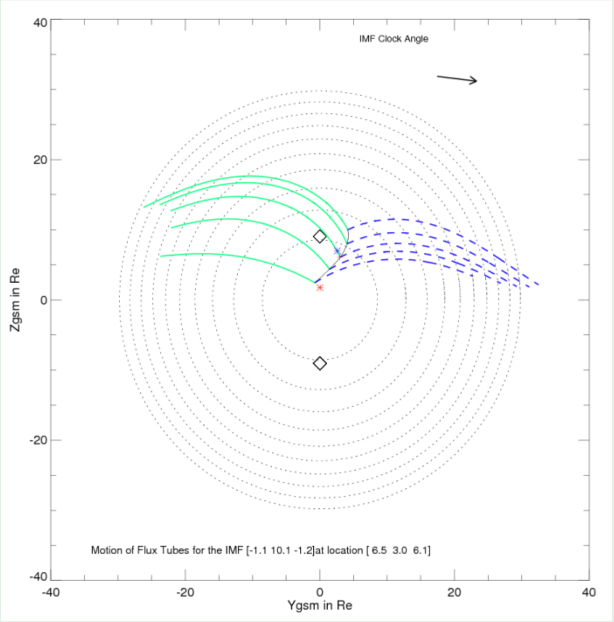
C2 sees multiple reversals of B_L; (C1,C4 see 2 reversals); C3 in magnetosphere.

Consistent with anti-parallel reconnection site.

Possible secondary X-line formation during low latitude MR?

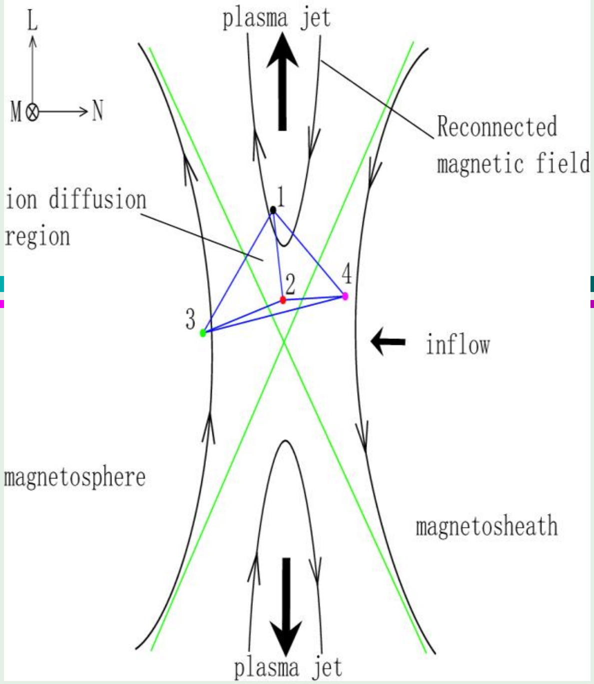


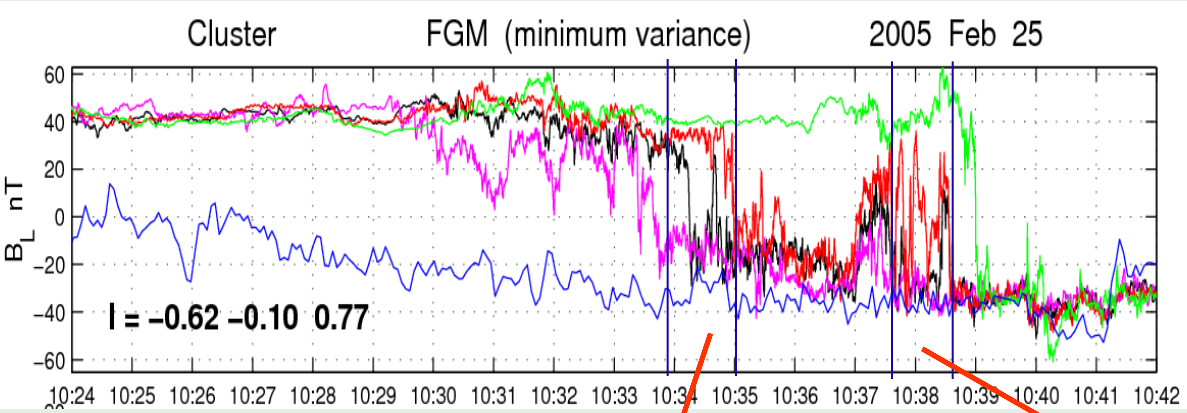


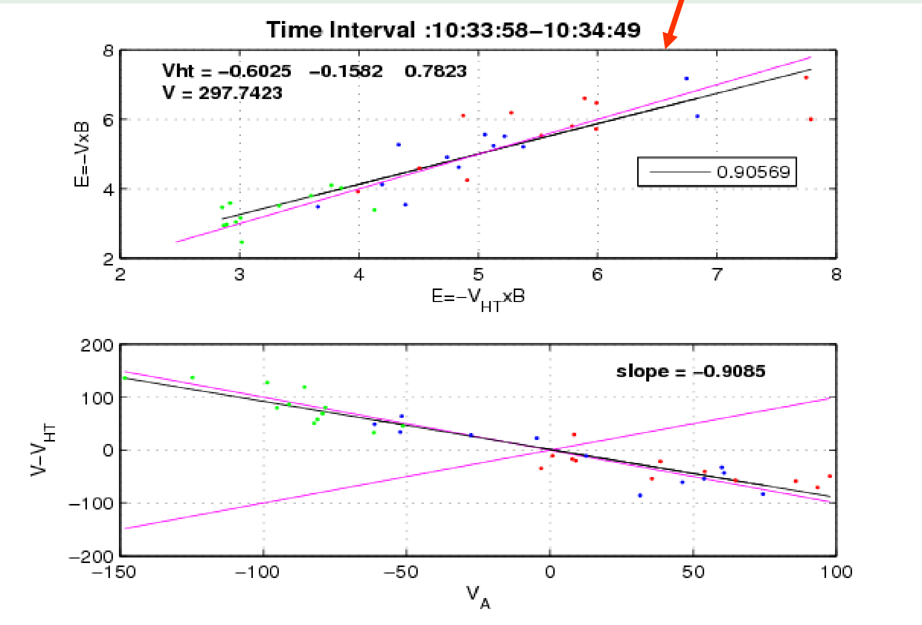


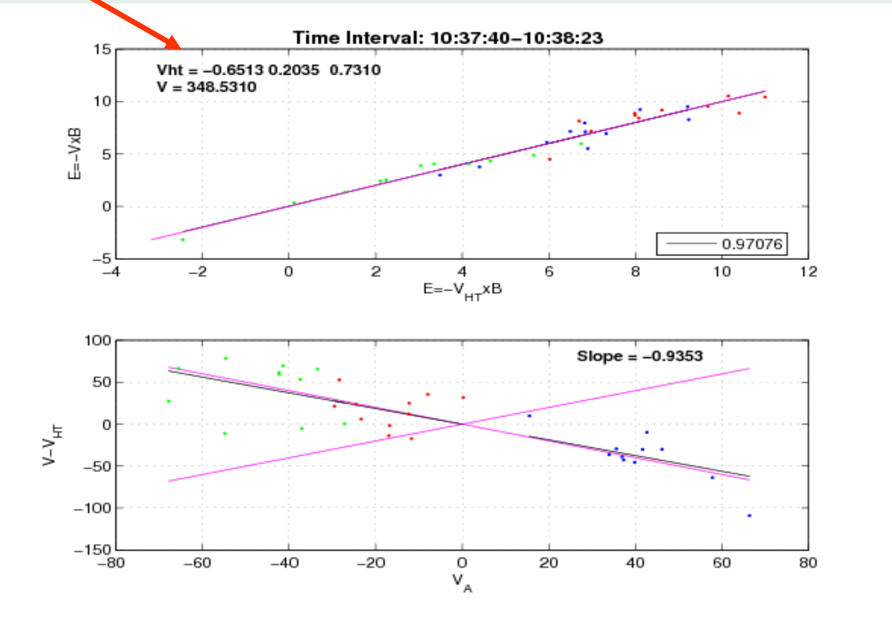
Cluster direct sampling of X-line?

Walen test confirms reconnection induced stress, aligned to a By dominated configuration









Themis-Cluster-Double Star conjunctions

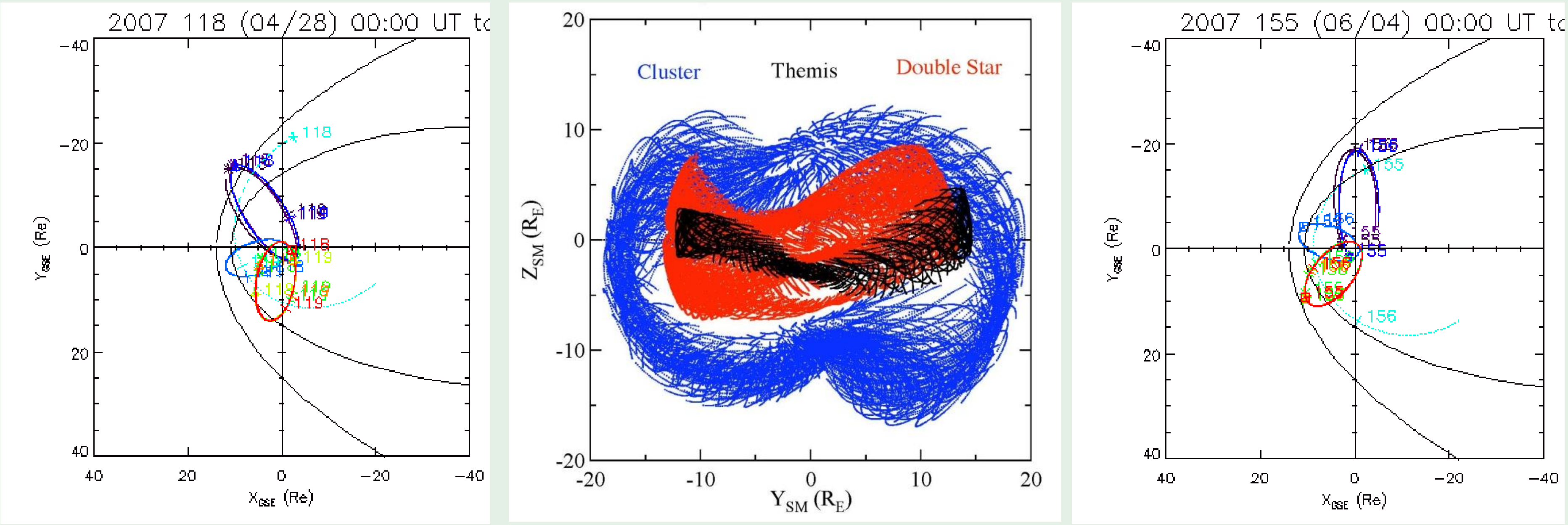
Configurations of the five Themis (red), four Cluster (blue), Double Star TC-1 (light blue) and Geotail (cyan) spacecraft in April 2007 (left) and June 2007 (right).

- During April/May TC-1 lies nearer noon and Cluster exits into the magnetosheath at the dawn terminator.
- The five THEMIS spacecraft in their string of pearls repeatedly skim the magnetopause at the dusk terminator.
- The middle panel shows orbit track segments within 2 hrs of a nominal magnetopause March to March 2007-8.
- Nearly the whole of the magnetopause is potentially covered:

  THEMIS (black) scans the dusk-side

  Cluster scans the dawn-side

  TC-1 moves midway between them in LT.



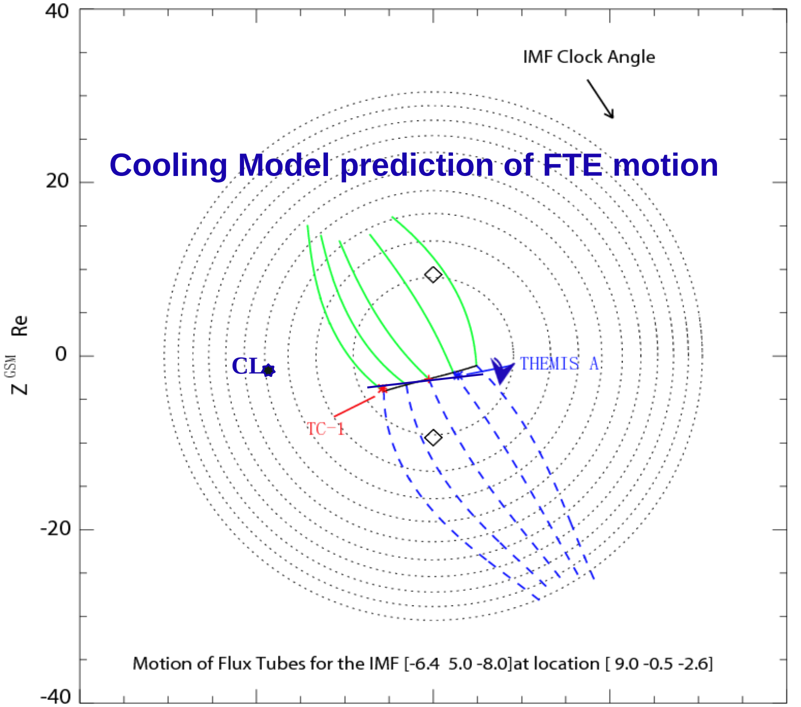
TC-1 and TH-A crossing: both north of X-line

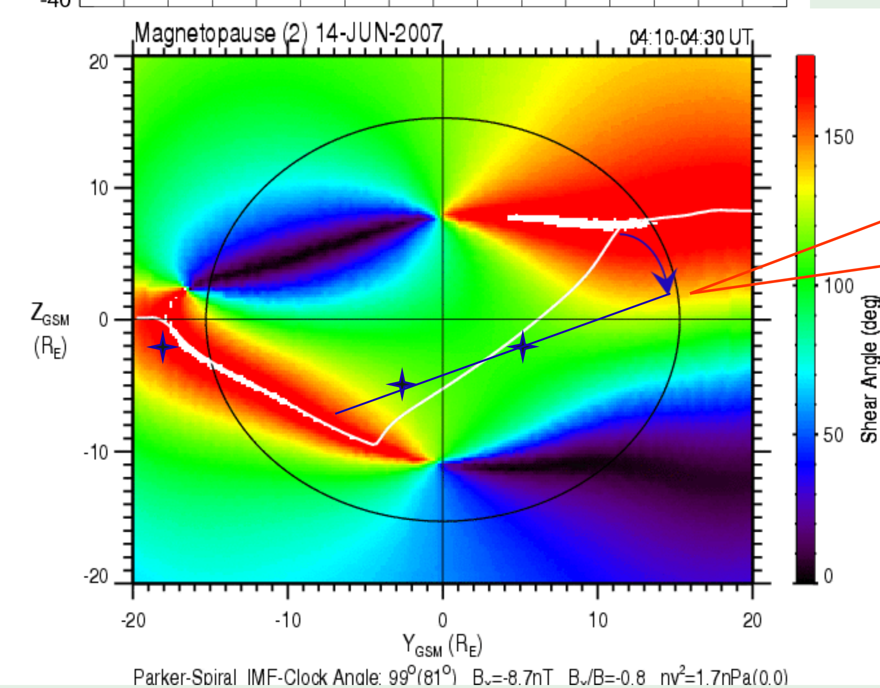
Both lie very near reconnection region at the same time.

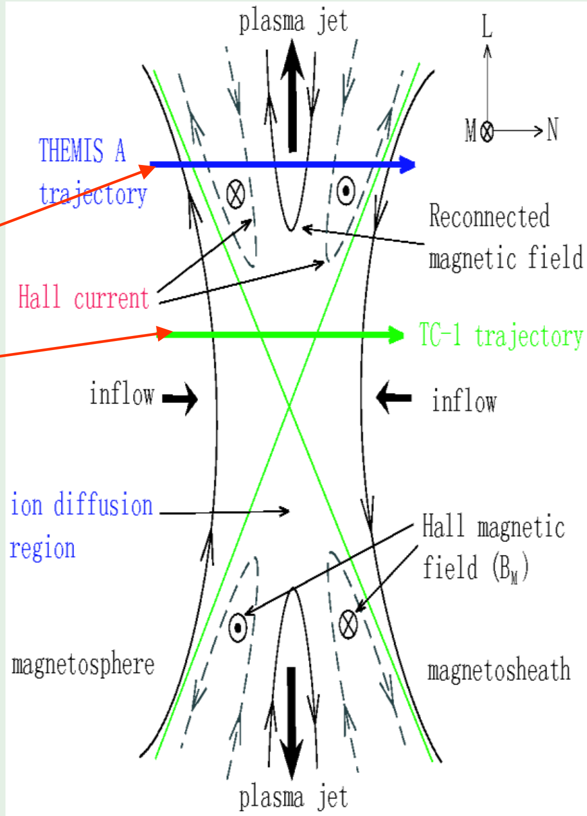
TC-1: Propagation time and distance from X-line: 3 s; 0.1 Re
Speed and direction of the FT motion: 222 km/s
(-0.22, -0.71, 0.69)

TH-A : Propagation time & distance from X-line: 35 s; 1.94 Re
Speed and direction of FT motion: 190 km/s
(0.03, 0.05, 0.99)

Modelled, mapped prediction of tilted X-line (component driven) consistent with s/c locations: possible rotation with IMF.





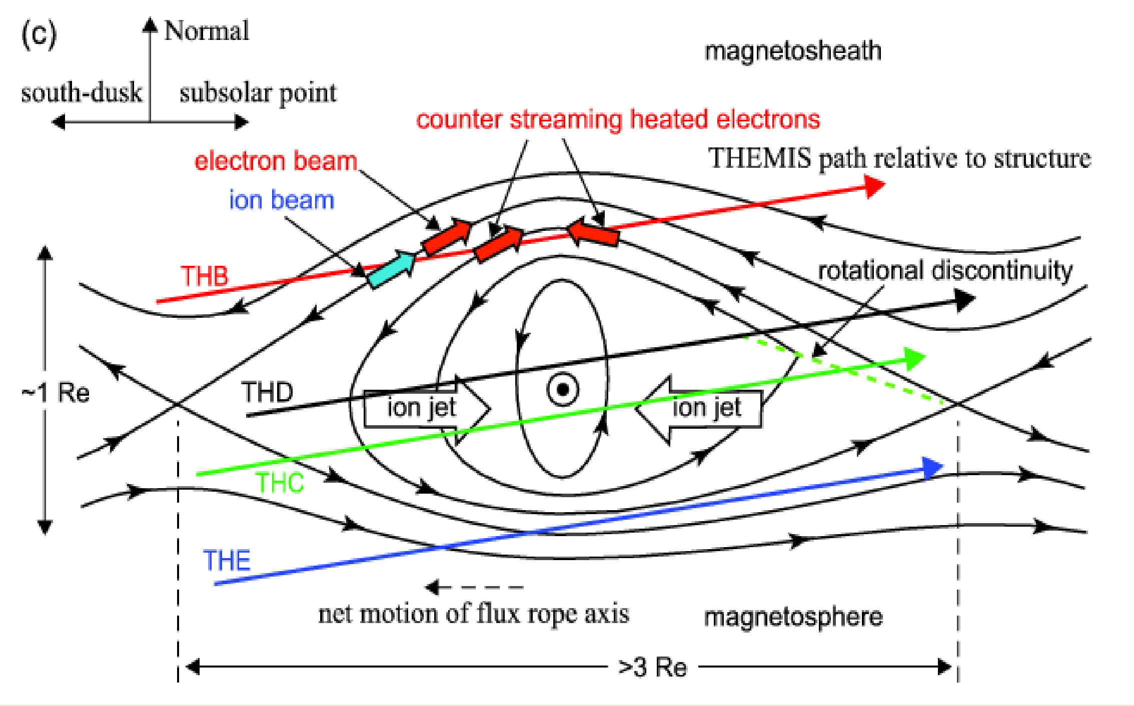


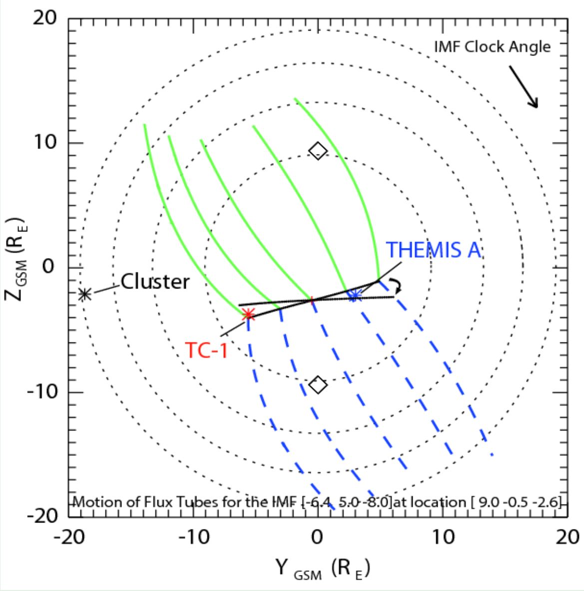
14 June:

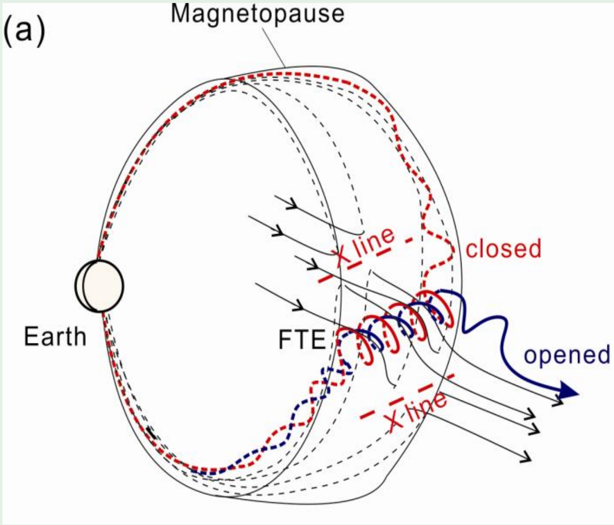
earlier MP crossing

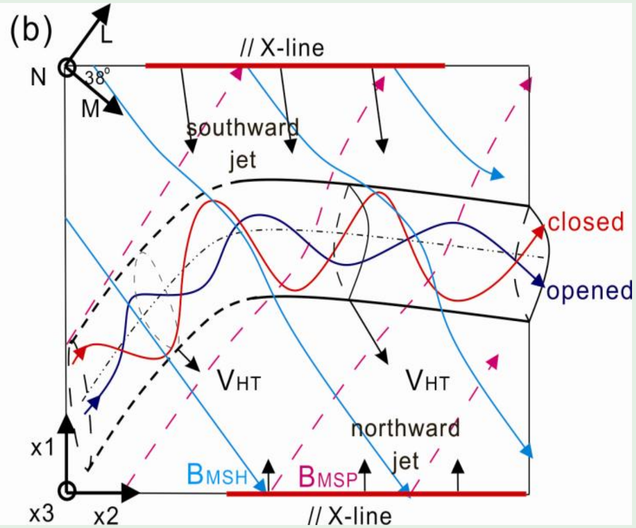
Zhong et al. 2012

- FT reconstruction (Grad-Shavranov: 2-D)
- Corresponding, incoming fast flows and well ordered Walen relations either side of signature: suggestive of MXL (sequential formation).
- Benefit of multi-spacecraft coverage through the structure: but G-S fit is on THC and THD.
- 2-D G-S plane is aligned to X-Y_{GSM} : THC/THD sample M'spheric branch of FT.
- Time shifted tracks show FTE is rolling along MP, dusk-ward with THB on the m'sheath side.









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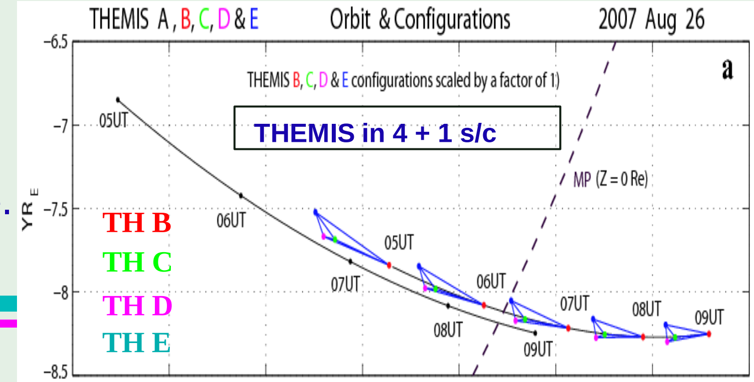
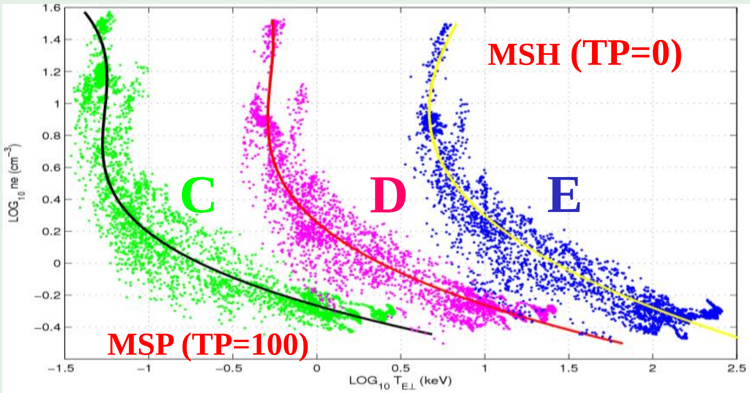
26 Aug: THEMIS BL, near X-line

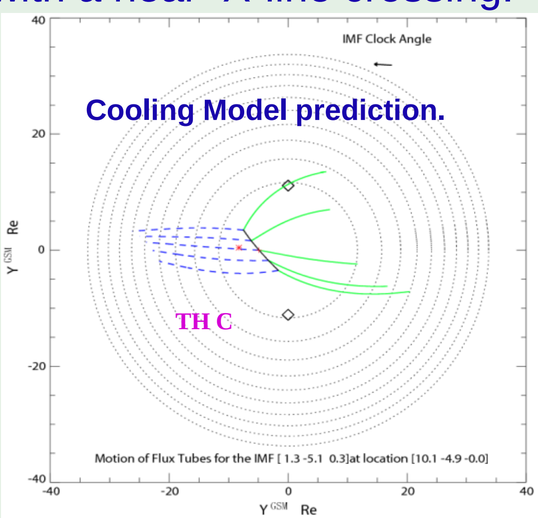
- LLBL observed by THEMIS: strong IMF By (+/-Bz).
- B, C, D & E observed similar signatures: Th-A inside.

Zhang et al. JGR, 2012.

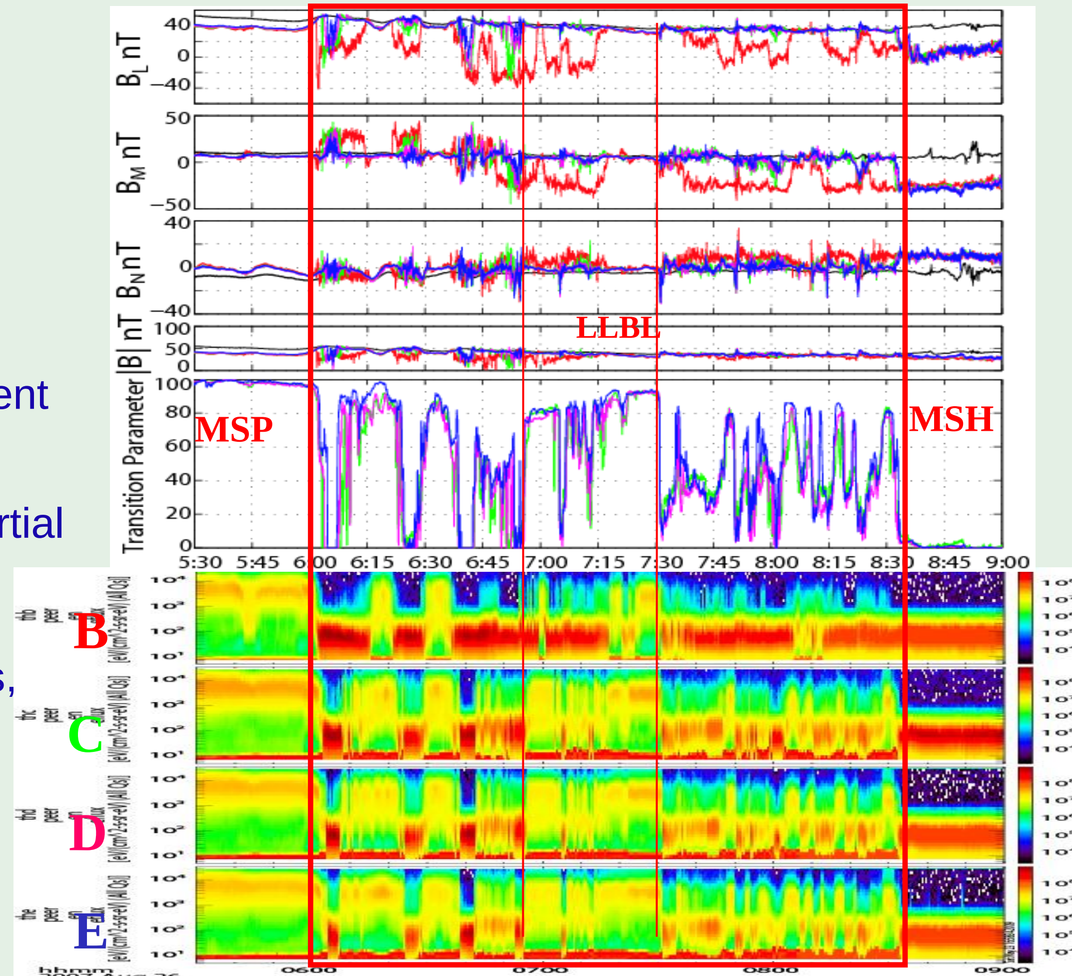




Transition parameter orders the MP well. Reveals clear plasma populations consistent with a near X-line crossing.



Multiple partial exits show similar distributions, but under twisted field geometry.



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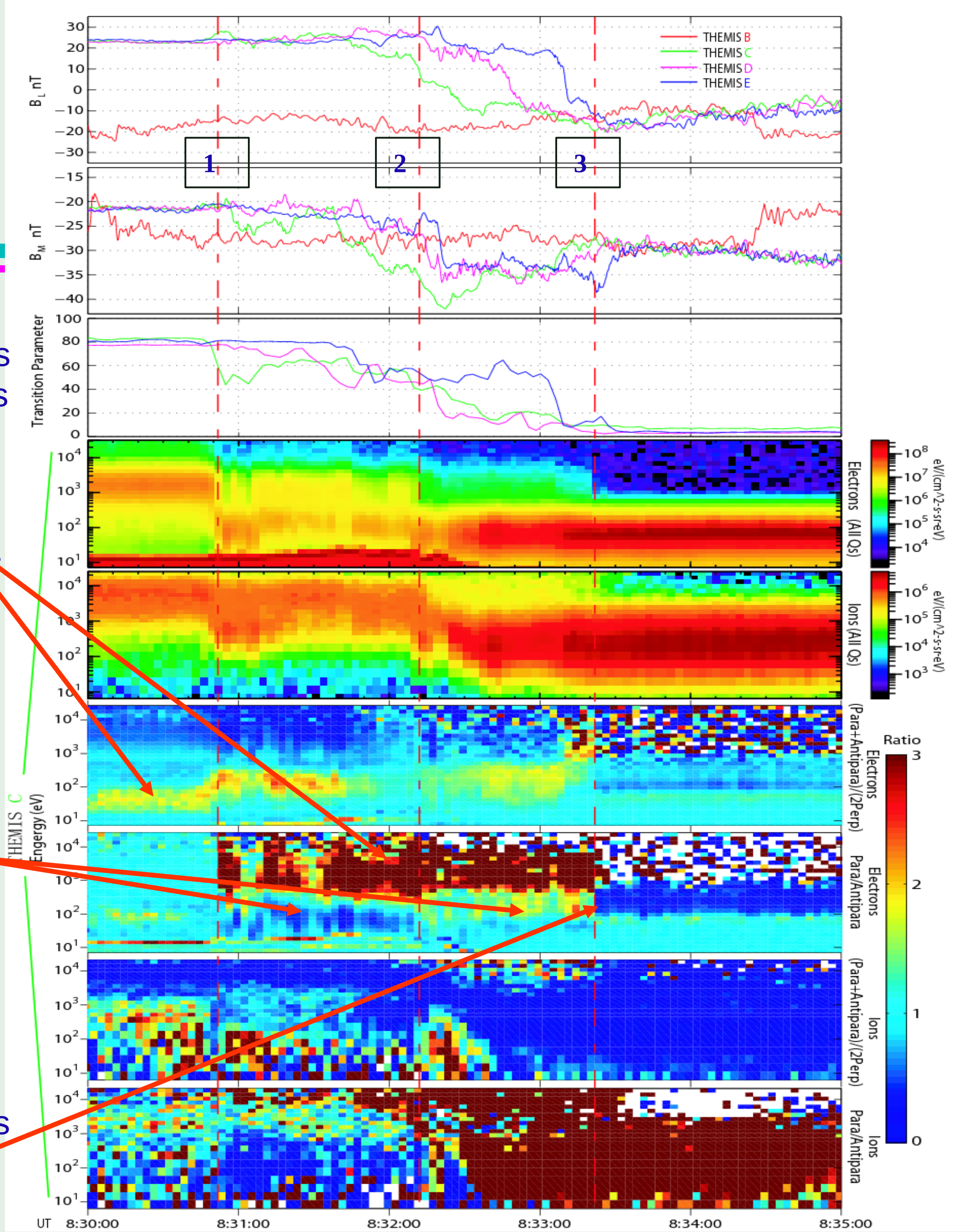
26 Aug:

THEMIS BL, near X-line

Last exit into magnetosheath shows bi-streaming and field aligned populations of ions and electrons (|| and perp anisotropy). TH-C is dawn-ward of X-line: parallel fluxes correspond to out-flowing particles.

1. Both electrons and ions show sharp open/closed field line boundary: from bi-streaming populations (recently closed) to out flowing magnetospheric populations.
2. Either side of the current sheet (MP) at the centre of the BL, magnetosheath electrons flow into the magnetosphere, and accelerated electrons flow away from the X-line. Some dispersion is apparent between recent and older reconnected field lines, which show the development of mirrored, magnetosheath populations.
3. Final exit into magnetosheath is marked by absense of magnetospheric electrons and ions.



'P': OCB, separatrix on MSP side (Ssp)

'Q': RD on the MSP side (RDsp)

'R': center of the current sheet (magnetopause), RD on the MSH side (RDsh)

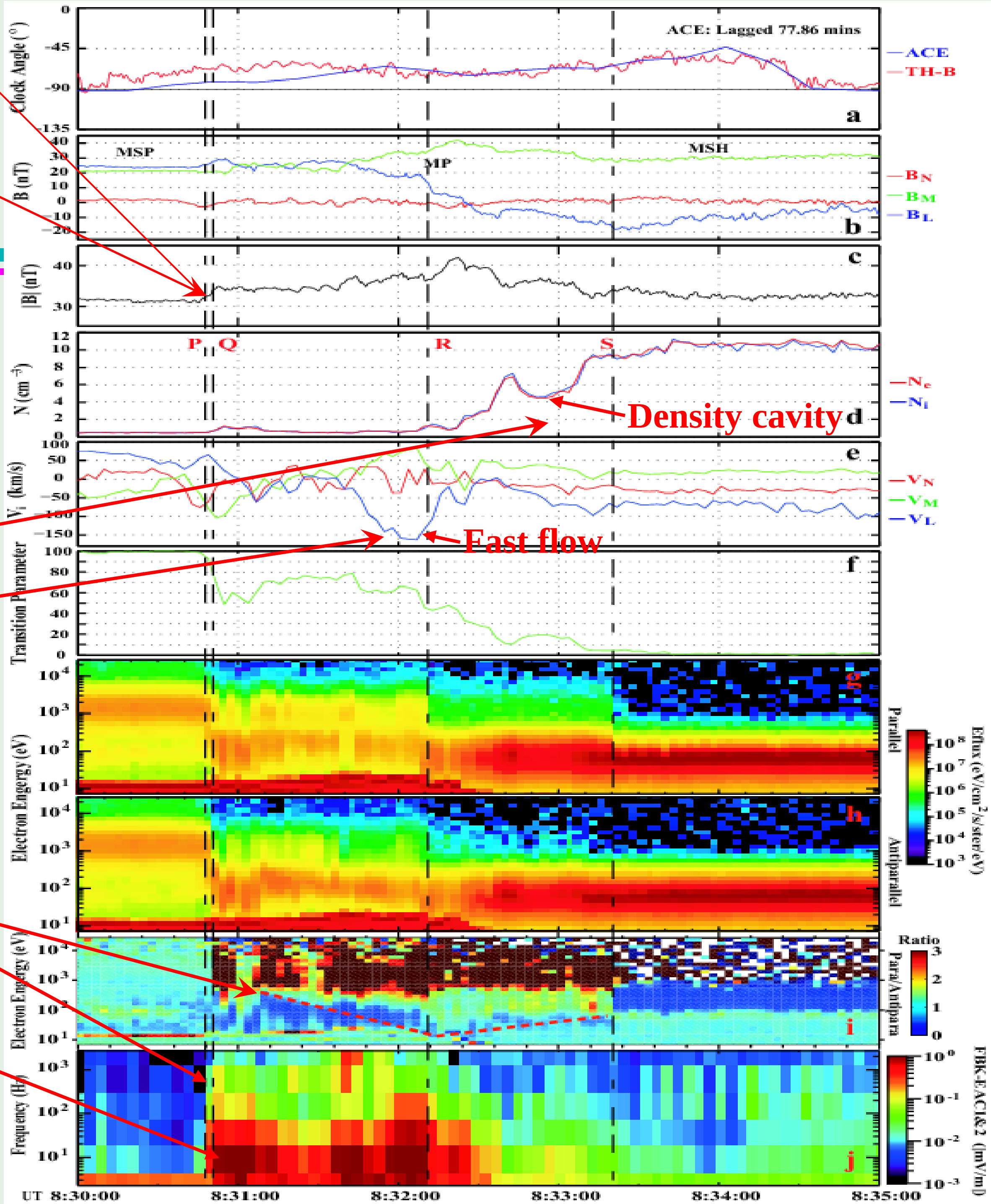
'S': separatrix on the MSH side (Ssh)

Single density cavity on the MSH side

Fast flow around the current sheet (MP)

"V" –shape distribution in low –energy electrons

A sharp boundary at P as the separatrix, E-field reaching max of 1. 1.35 mV/m, show RD at Q



‘P’: OCB, separatrix on MSP (Ssp)

‘Q’: RD on the MSP side (RD

‘R’: center of the current she (magnetopause), RD on the M (RDsh)

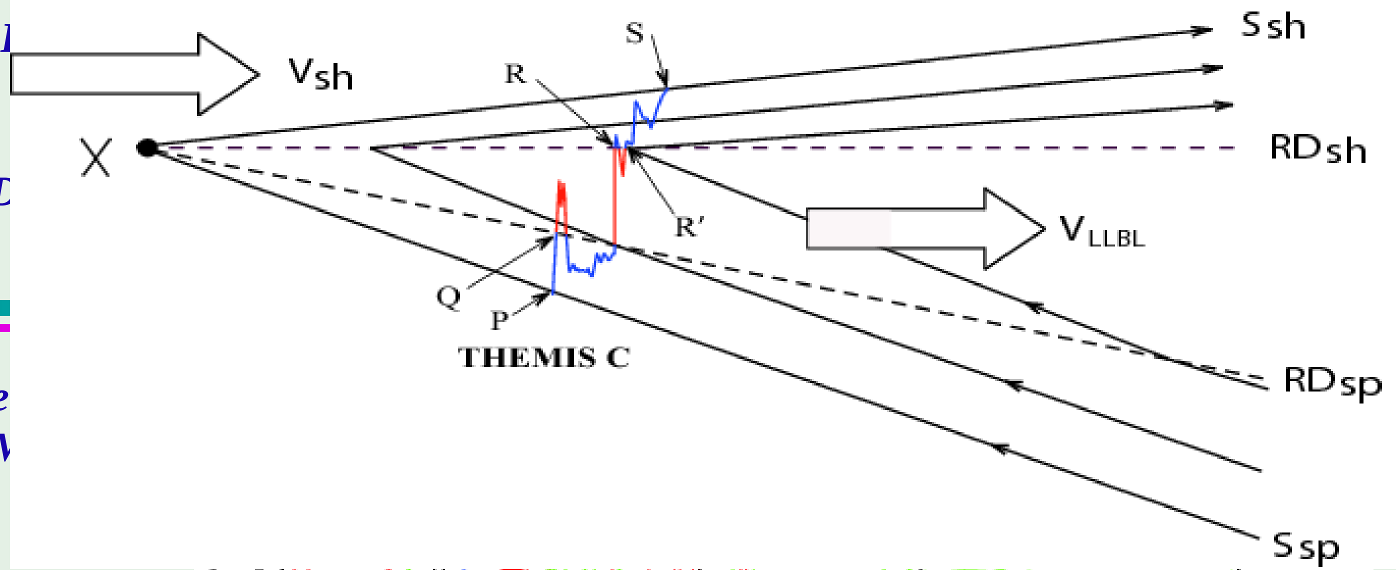
‘S’: separatrix on the MSH side (Ssh)

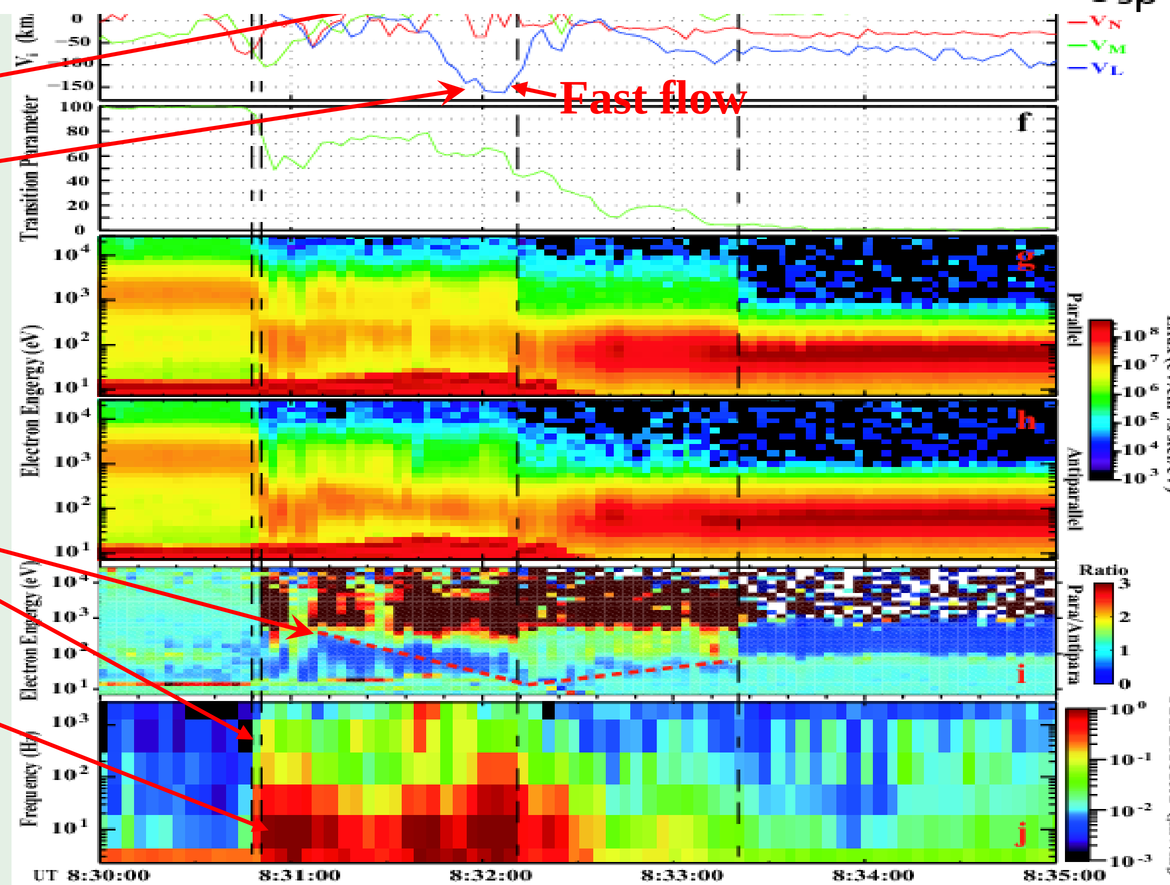
Single density cavity on the MSH side

Fast flow around the current sheet (MP)

“V” –shape distribution in low –energy electrons

A sharp boundary at P as the separatrix, E-field reaching max of 1. 1.35 mV/m, show RD at Q



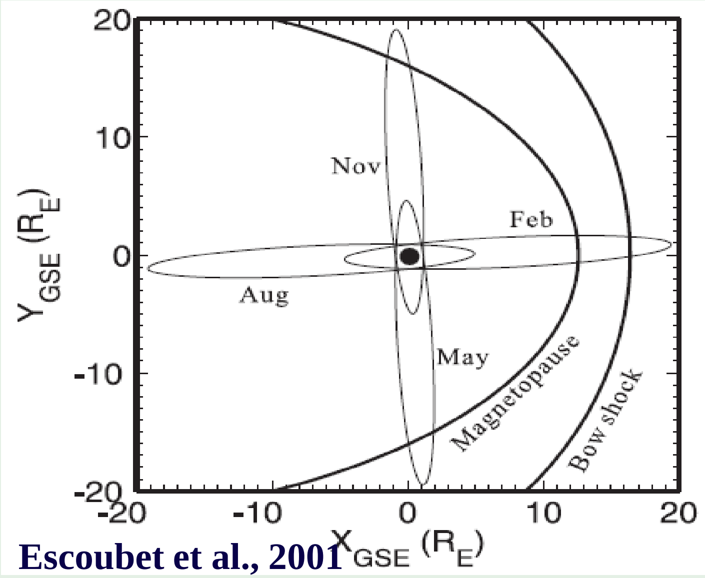


Cluster experience: current density

Cluster has often crossed the RC during its 13+ years of operations.

Each RC crossing will also encounter adjacent FACs.

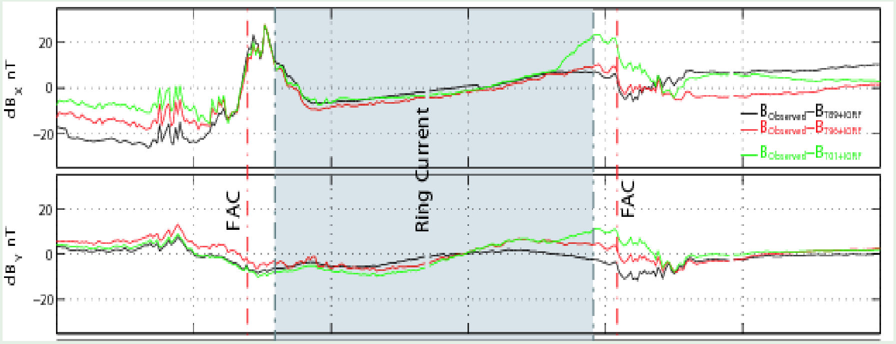
Suitable for spot checks of RC strength.

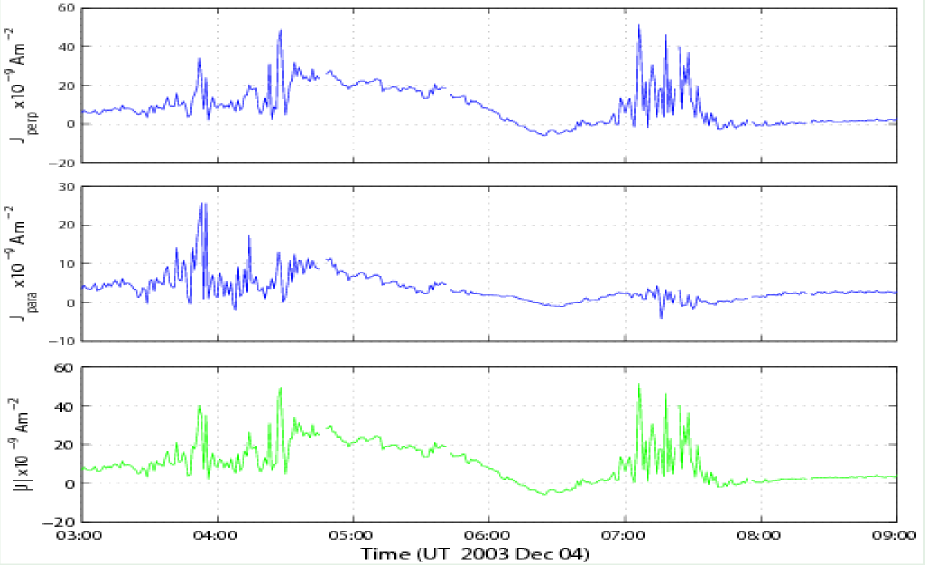


Escoubet et al., 2001

Curlometer: point by point calculation

(divB , s/c configuration and temporal stability).





Direct curl B calculations can identify the FAC structure and Ring Current :

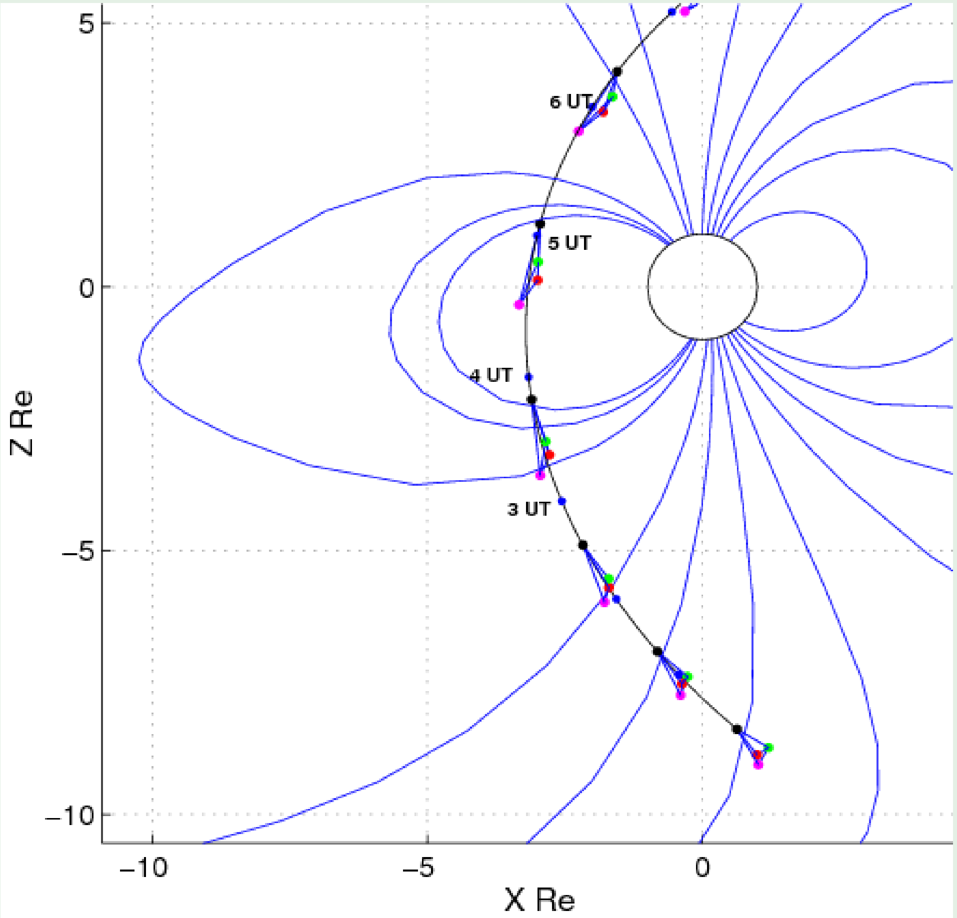
•Filamentary small scale signatures: some are FAC, but not all, and temporal behaviour is often present.

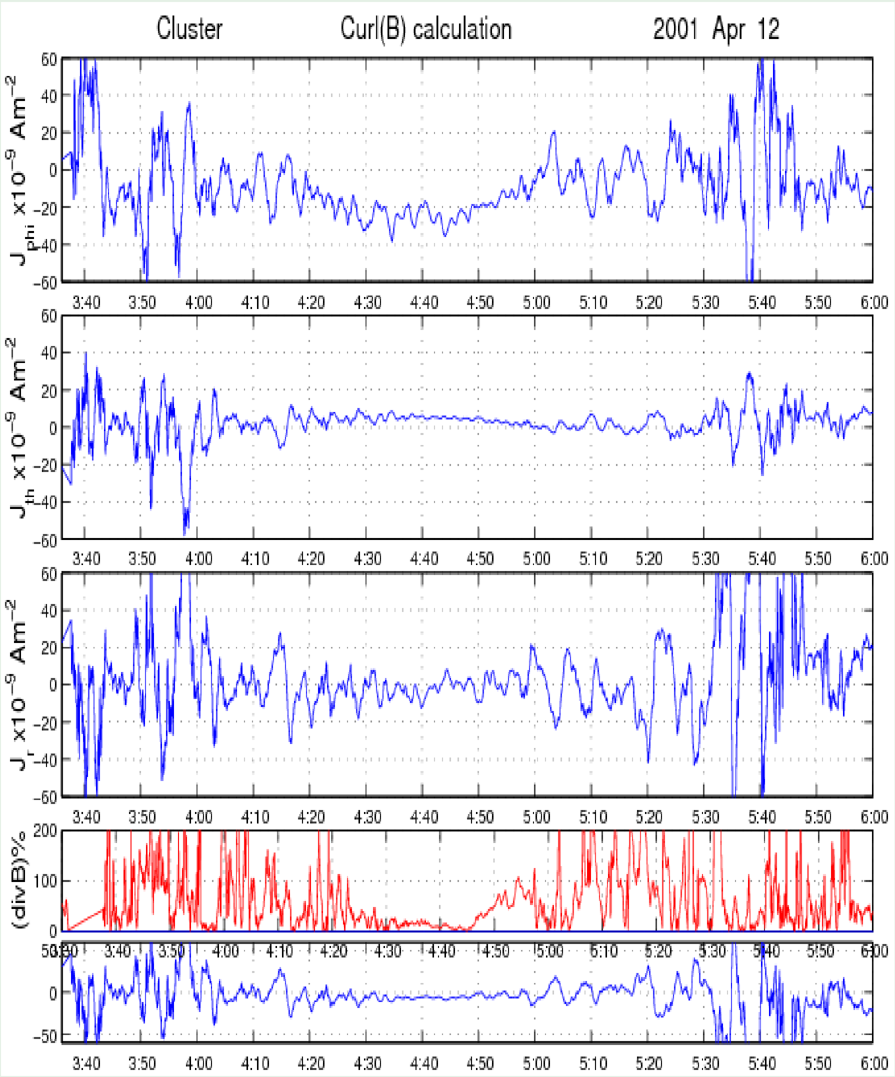
•Ring current is generally well defined, but requires particular constellations for high accuracy.

Could also test Swarm FAC ‘curlB’ method using pairs of Cluster spacecraft and comparison to the full curlometer (4 s/c).

Ring current analysis: FAC

- Often alignment is with J_{phi} inside RC and close to FAC outside
- Non-linear gradients in 'dipole' field affect linear estimators
- Curlometer stable against these effects: subtract 'zero current' model field





Comparison to LEO measurements:

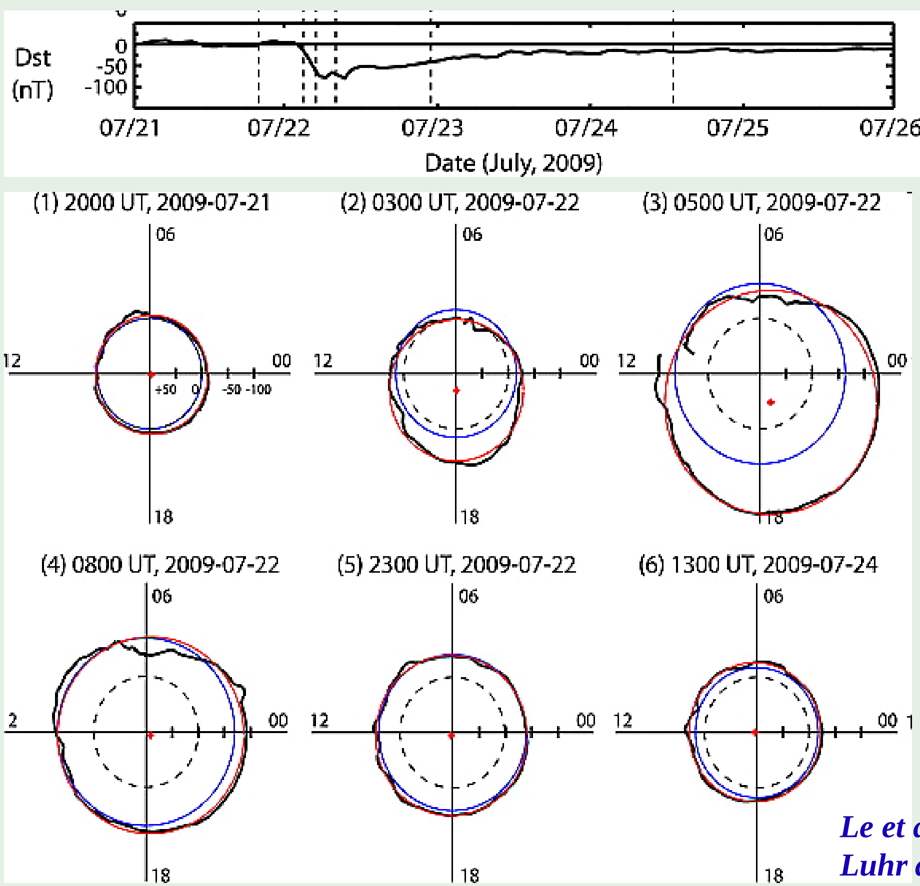
Low-Earth, equatorial satellite C/NOFS shows a local time dependence of the ring current field during quiet and disturbed conditions (strong, dusk-side enhancement).

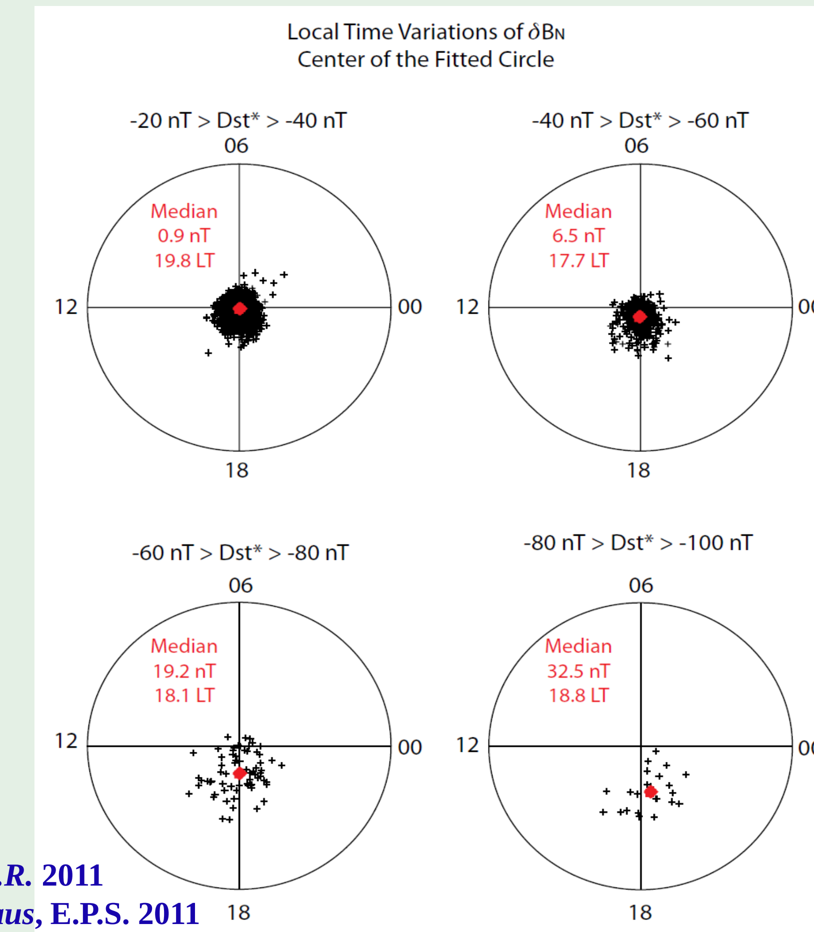
Fitted data (left) are during a typical storm sequence

Plots are the locus of each residual δBn around LT, centred on the fitted dashed circles (δBn=0).

Red circle and centre points fit the blue data trace; centre points are shown statistically on the right.

Blue circles represent the prevailing Dst for each UT.



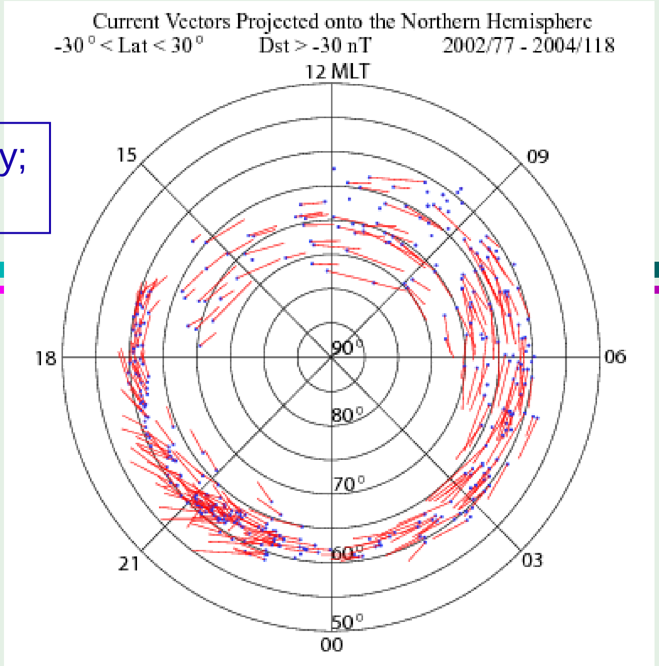


***Le et al., J.G.R.* 2011**

***Luhr and Maus*, E.P.S. 2011**

Ring current analysis: statistical trends

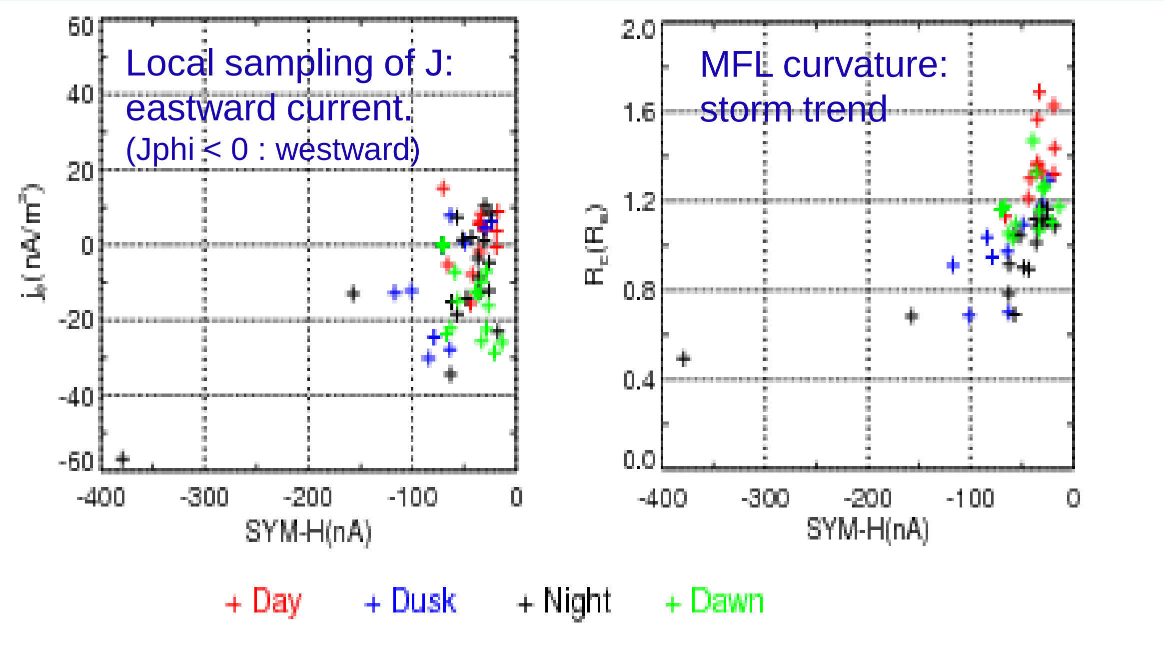
Right: Mapped Cluster crossing locations: (top) mapped current density; (bottom) corresponding auroral model zone for kp~2.

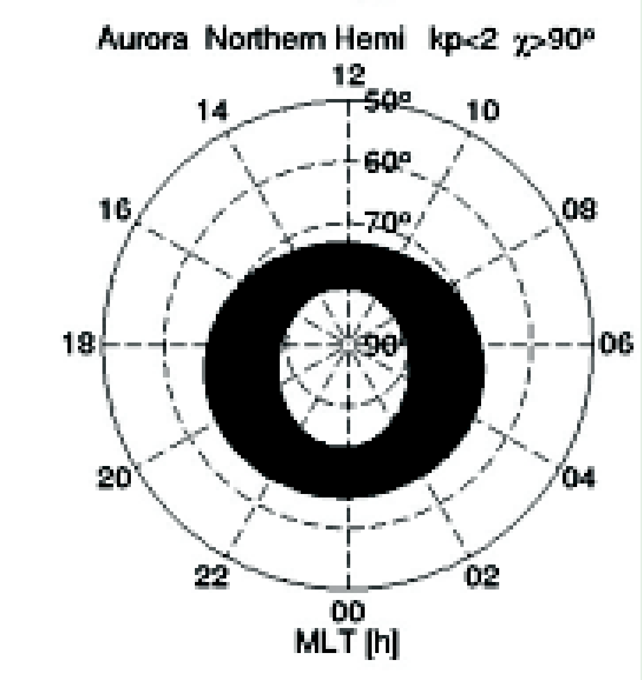


Cluster coverage extends to equatorward edge of Auroral zone

Below: statistics for storm time current density and field curvature estimates.

LT asymmetry reverses for stronger activity.





Advanced analysis tools:

Magnetic field gradients from rotation and curvature properties of the magnetic field.

Generalize use for 2-5 spacecraft: reliable estimates of some components of J.

Three main applications of gradient analysis (no timing assumptions):

- Generalised method to calculate spatial gradients from 3-5 spacecraft: suitable for distorted spacecraft constellations and when 3 spacecraft are available (partial result, e.g. one J component).
- Full gradient estimates for at least 3 spacecraft in the case where FA currents are expected.
- Use of special constraints to obtain full magnetic gradient from at least 2 spacecraft

Comparison to standard 'curlometer' methods which employ time shift analysis along orbit track (e.g. *Ritter et al. 2006*, *Grimald et al., 2012*):

- Swarm 'vertical' curlometer: allows a check of FAC component.
- Comparative Cluster analysis from 2-3 spacecraft (in-situ RC and FAC coordination)

Key assumptions for special gradient analysis:

Based on Barycentric coordinate representation of the dyadic of **B**, $\nabla\mathbf{B}$, applied through diagonalisation of the volumetric tensor for the spacecraft constellation.

3 s/c FAC:

$\boldsymbol{J} = J_{||}\boldsymbol{b}$; then may project the known component perpendicular to the constellation plane.

2 s/c full gradient:

Solenoidal condition: $\nabla.\mathbf{B} = 0$

Stationarity: $d\mathbf{B}/dt = (\mathbf{V}.\nabla)\mathbf{B}$; $\partial\mathbf{B}/\partial t = 0$

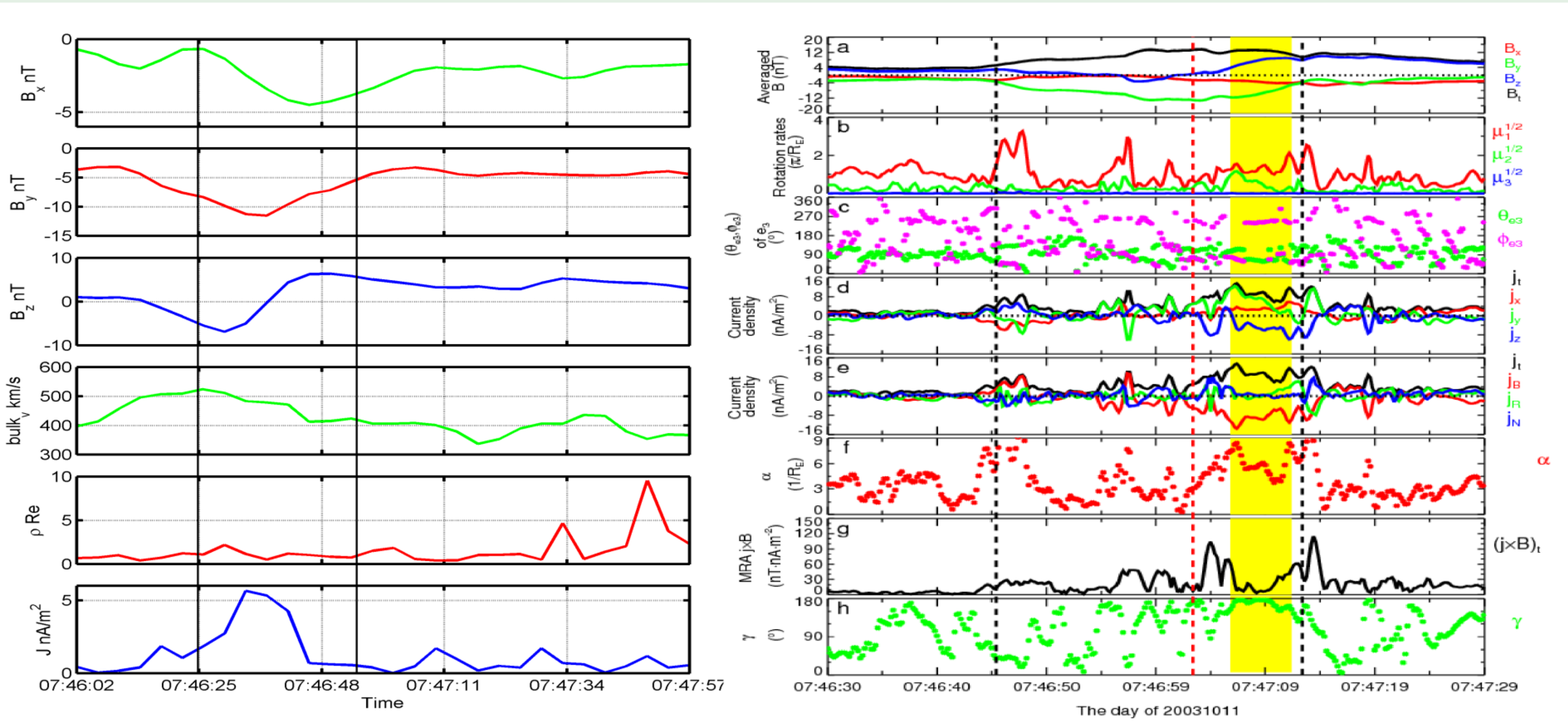
Force free: $\nabla_\wedge\mathbf{B} = \mu_0\mathbf{J} = \alpha\mathbf{B}$

For special orbit constellations, or if ***V*** is measured can obtain ideal solutions: tested with ideal dipole field and circular orbits.

Compare to 'curlometer' along Swarm obits.

Advanced analysis tools:

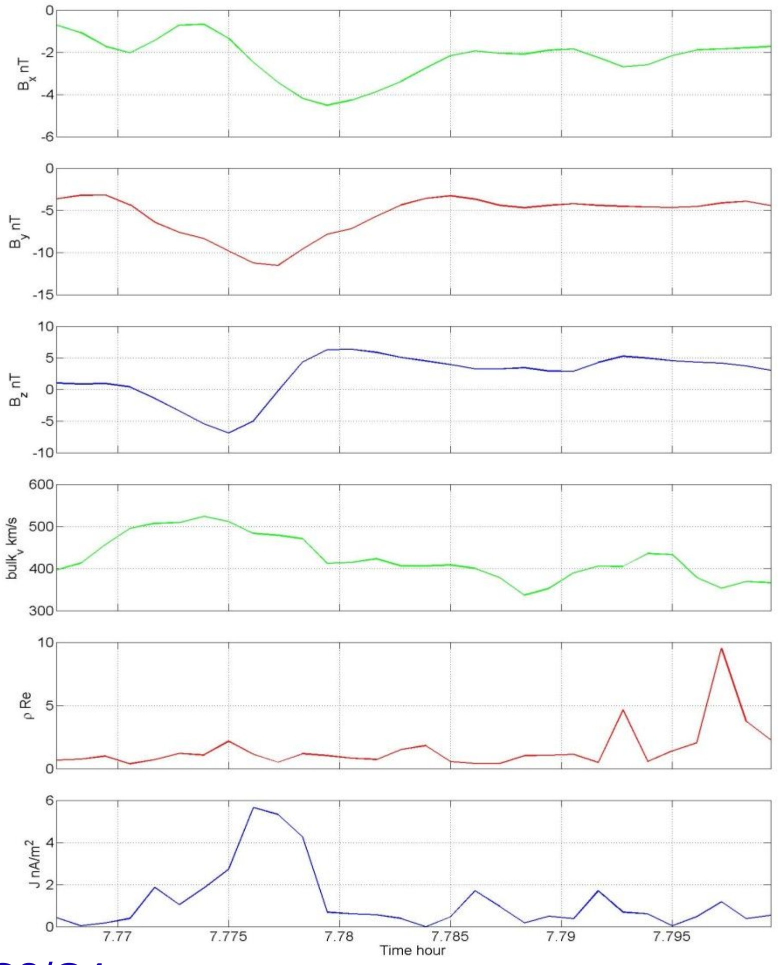
Two spacecraft demonstration: FT



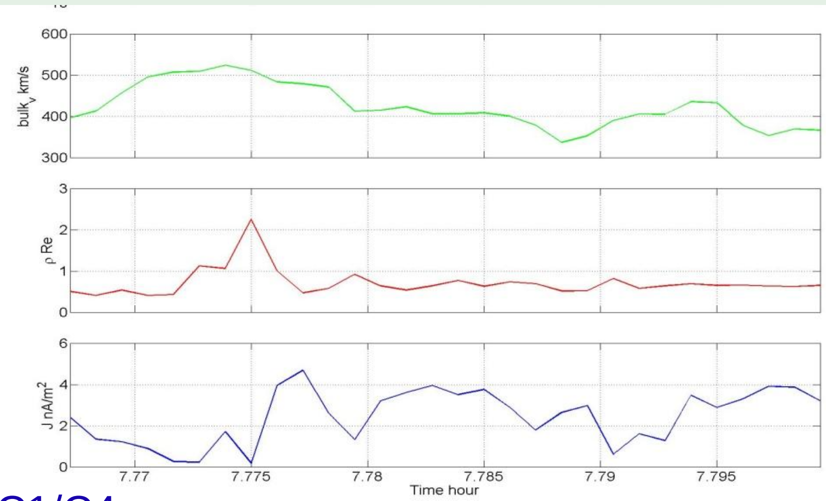
Comparison between the 2-point analysis result (left panels) and 4-point analysis result (left panels) on the 11 Oct 2003 tail flux rope event with the Cluster magnetic data

Advanced analysis tools:

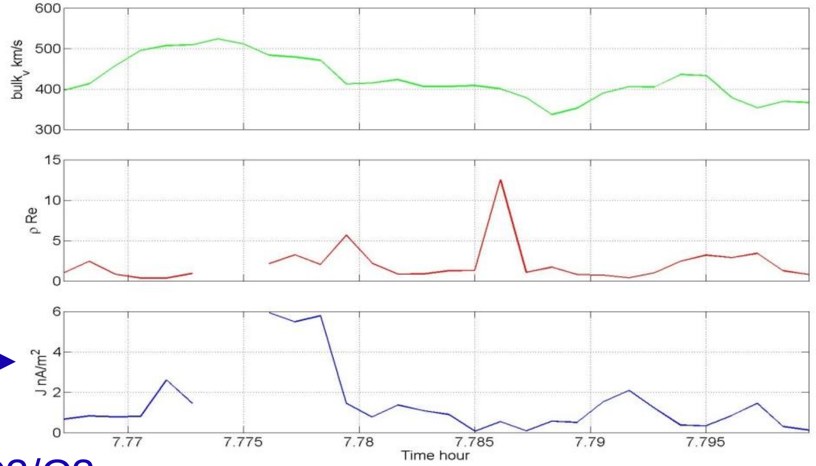
Two spacecraft demonstration: sensitivity of s/c pair.



C3/C4



C1/C4

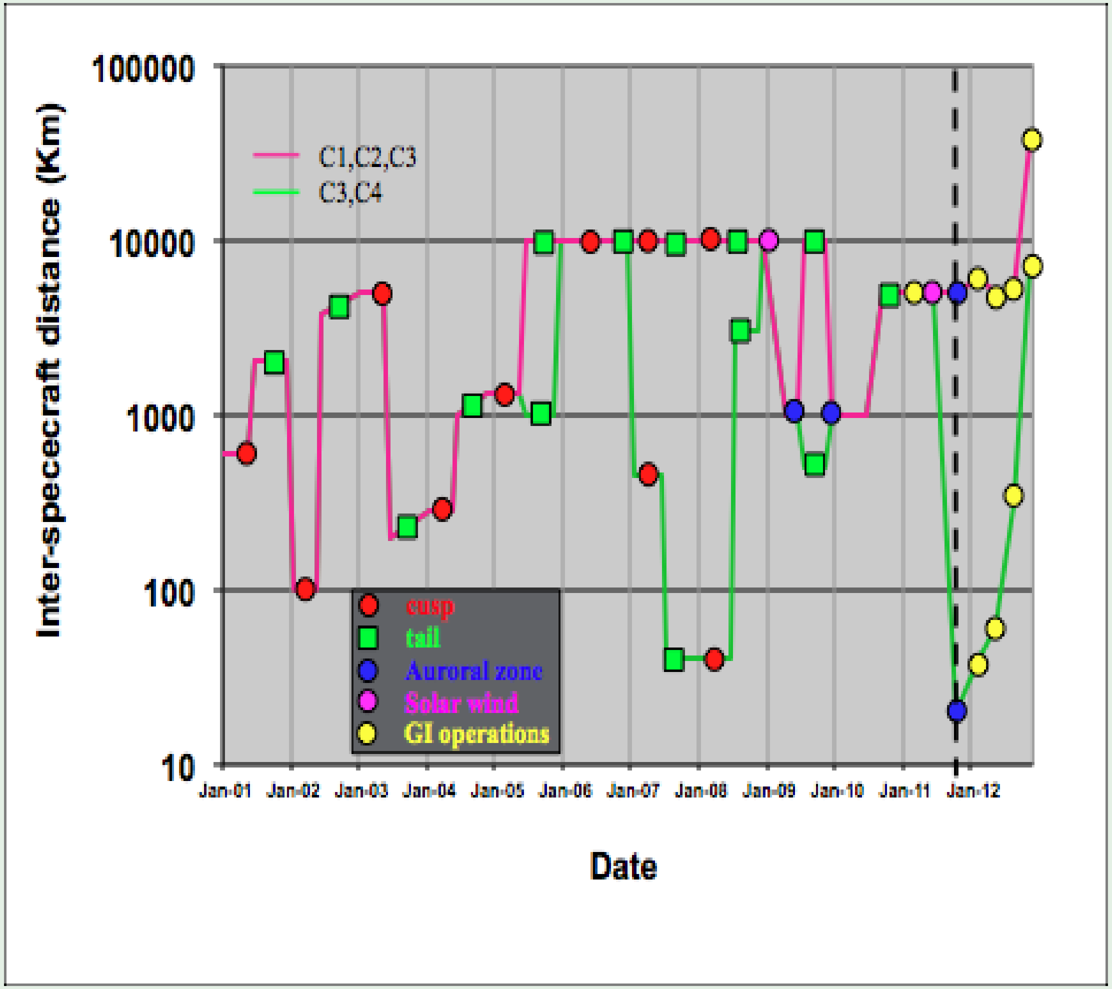


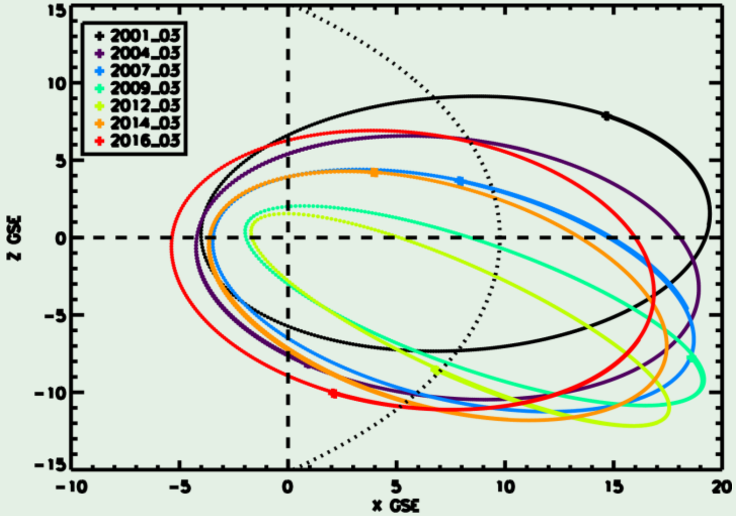
C2/C3

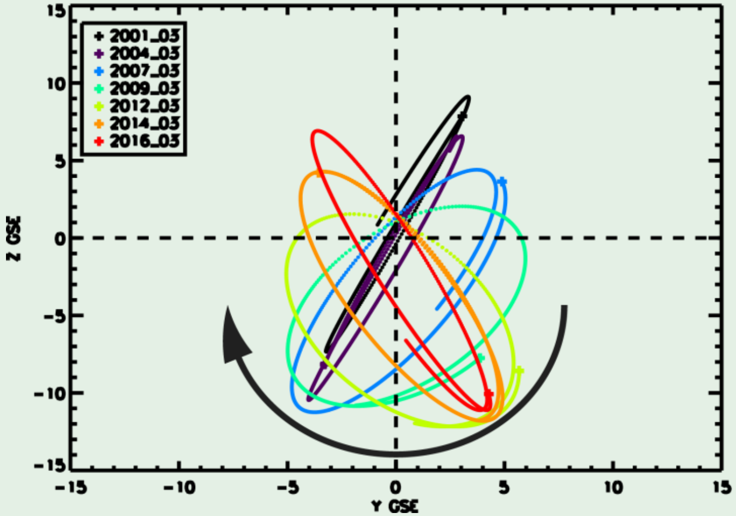
Swarm-Cluster coordination: separation strategy

Changing perigee height

Orbit roll-over, distorted constellations (multi-scale).

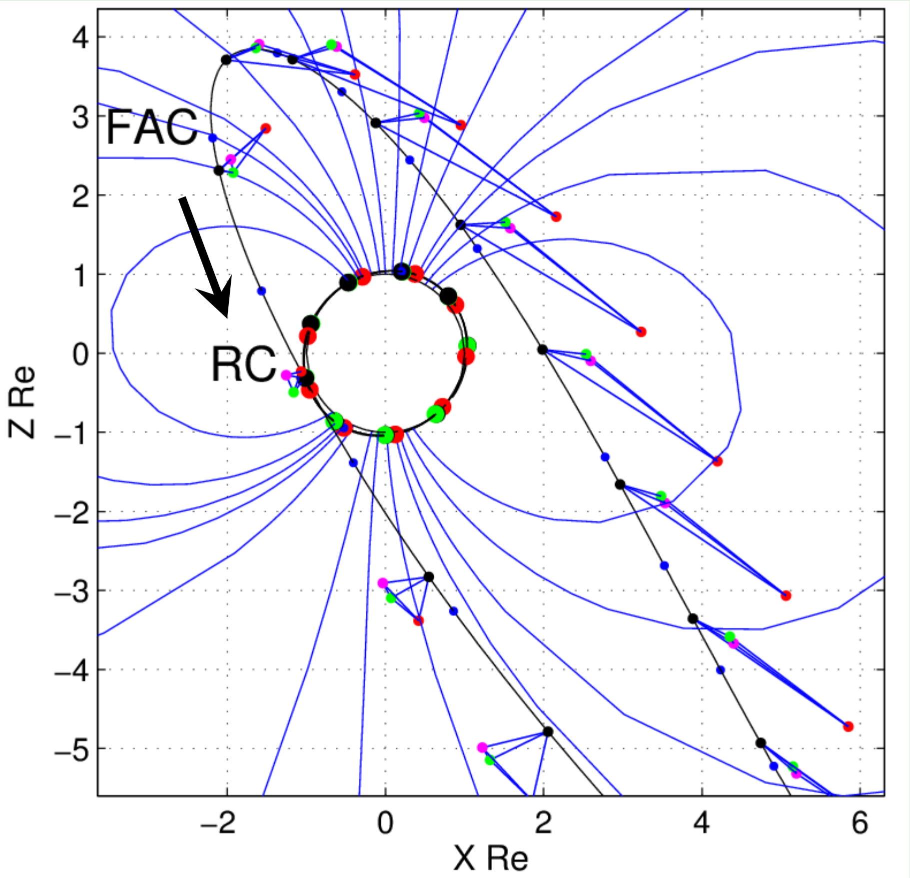


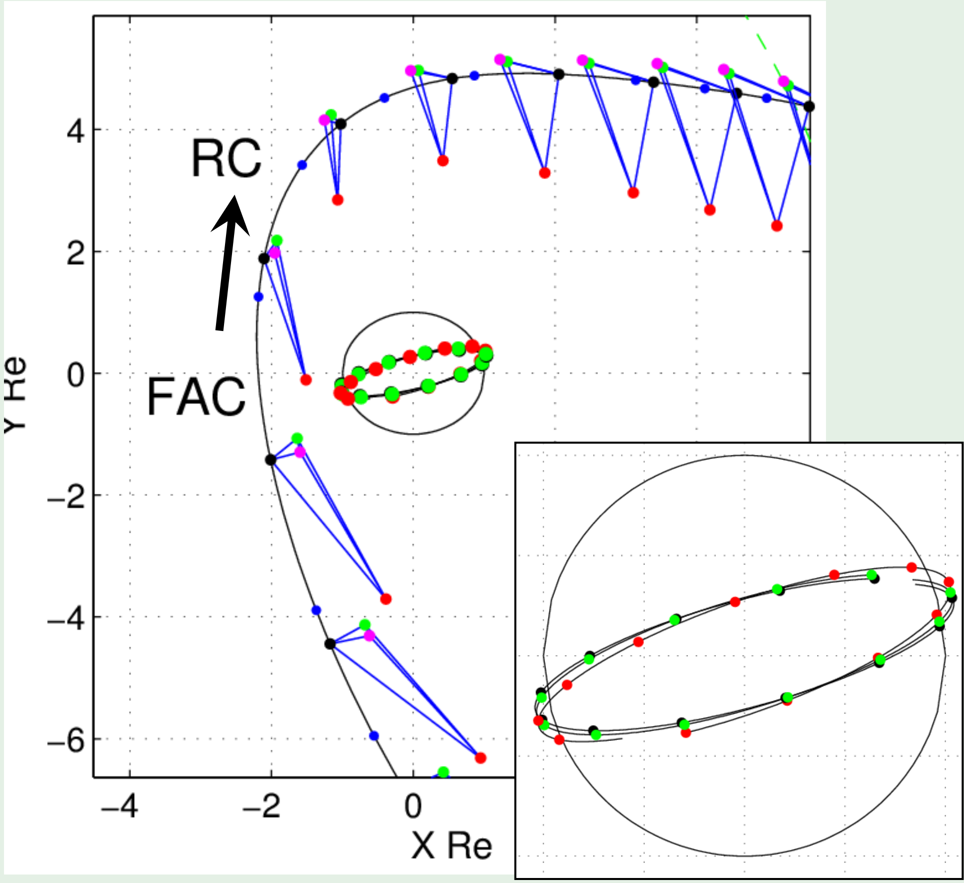




Cluster-Swarm Key configurations: 2014

Initial Cluster configuration set for the ring current: to access curl(B).
Orbit tilt samples range of LT giving good local coordination between Cluster and Swarm.
Accurately measuring curl(B) in FACs is difficult, due to the fine structure of the FACs.

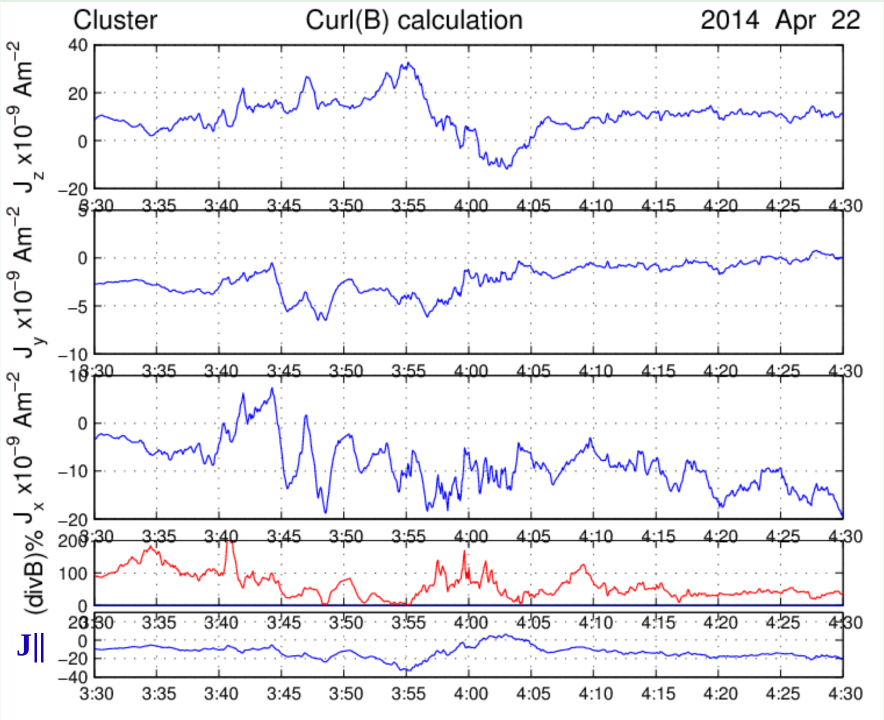


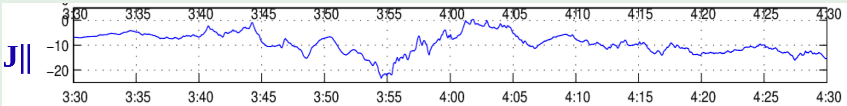


Example, 2014 April 24: shows small Cluster constellation during RC and close LT alignment with Swarm during Cluster FACs.
Inset shows close grouping of 3 Swarm spacecraft. (A, B, C = black, red, green)

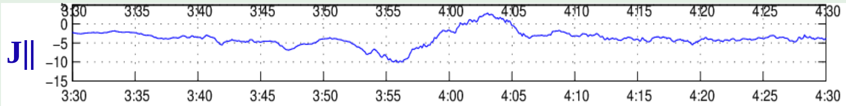
Comparison of FAC estimates: detail

Curlometer at cluster compared to 3 s/c
FA component for two s/c planes: persistent signature

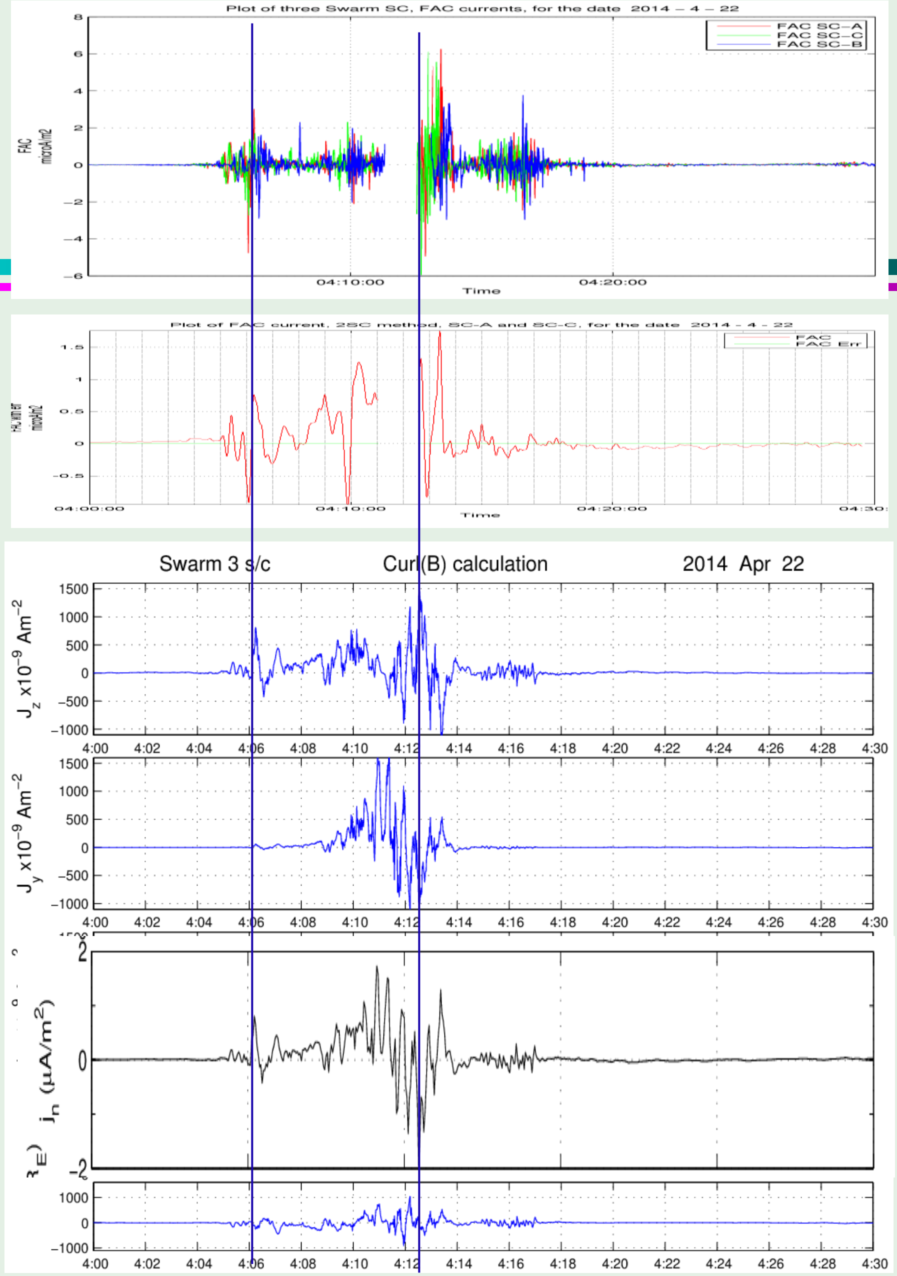




3,4,1



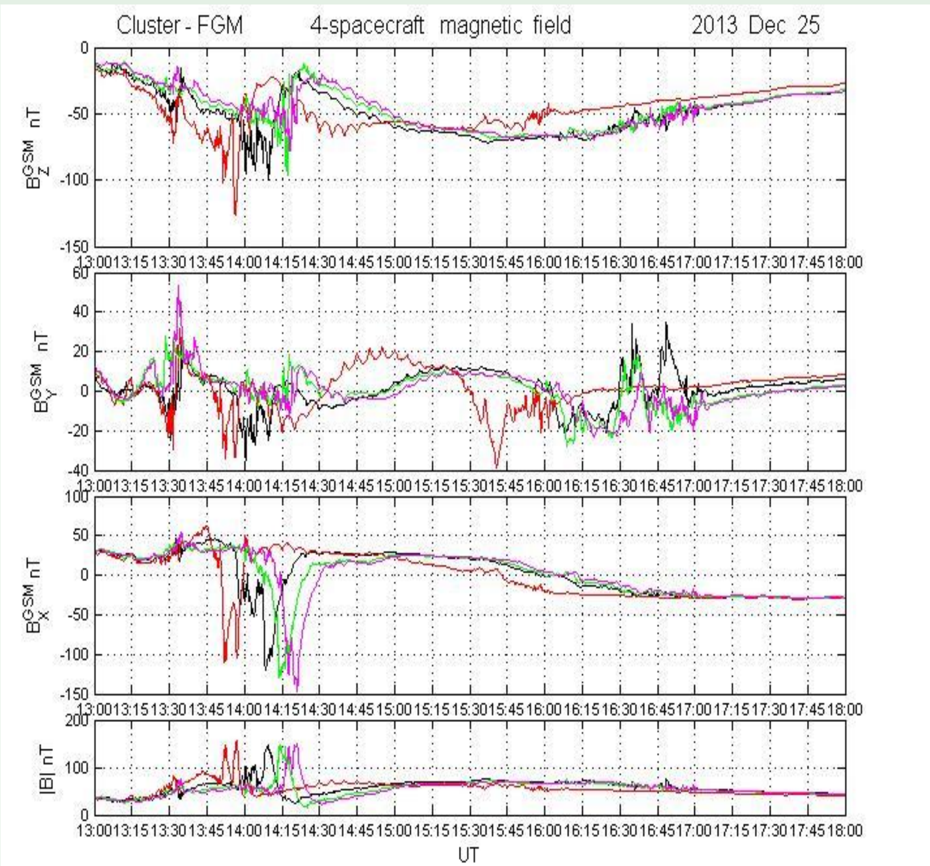
1,2,3

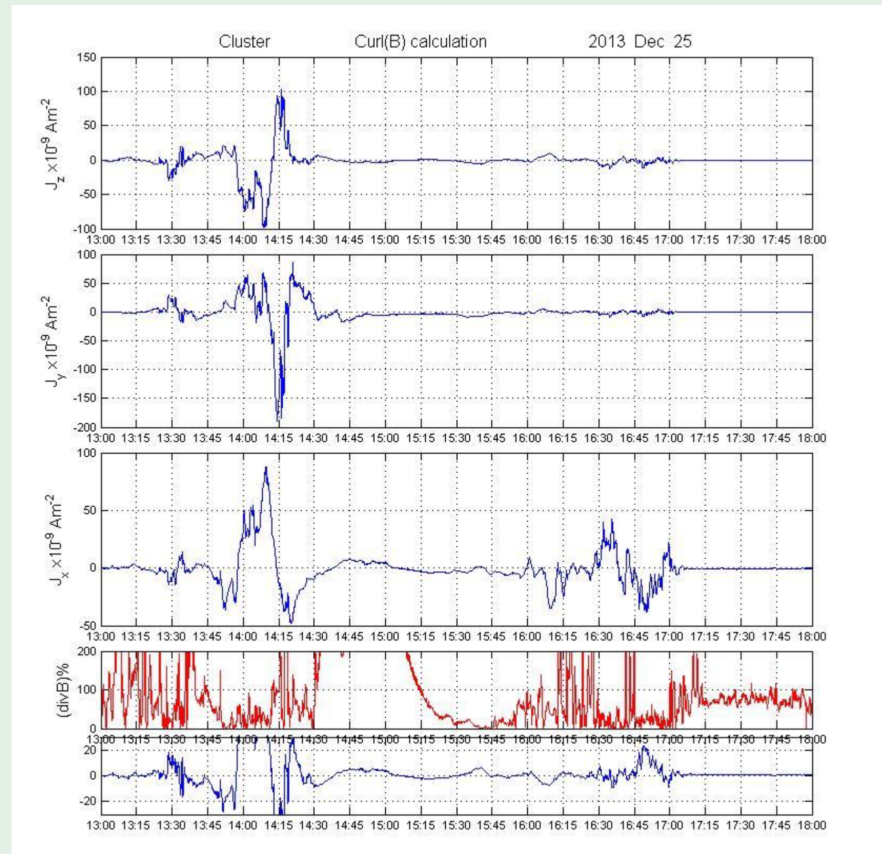


Example, 2014 April 22: Comparison to Curlometer 3 s/c estimate.
Application of gradient analysis to calculate current gives the same result.

Cluster-Swarm Key configurations: cusp

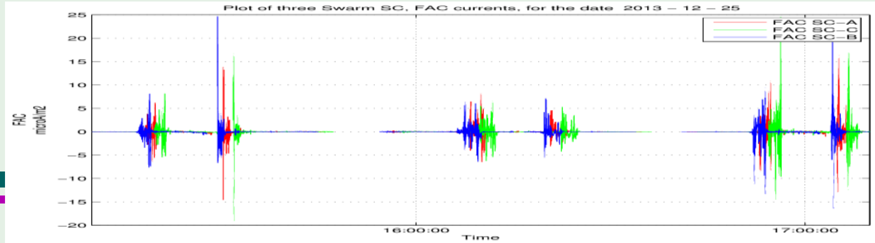
Second target for cusp encounter is more rarely encountered through the tilt in the cluster orbits, but achieves close configurations on the same orbits as the RC crossings.

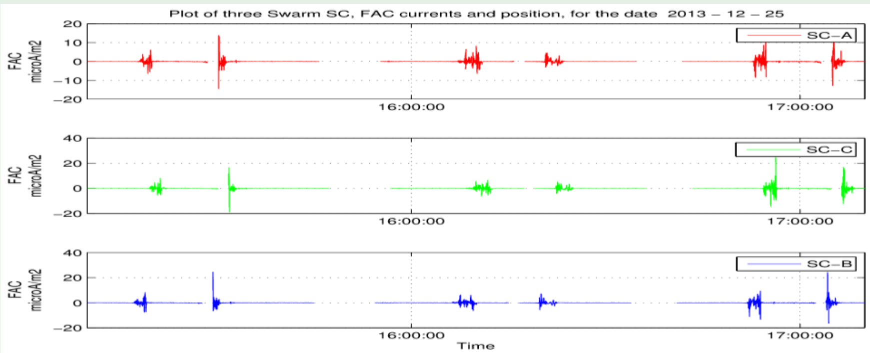


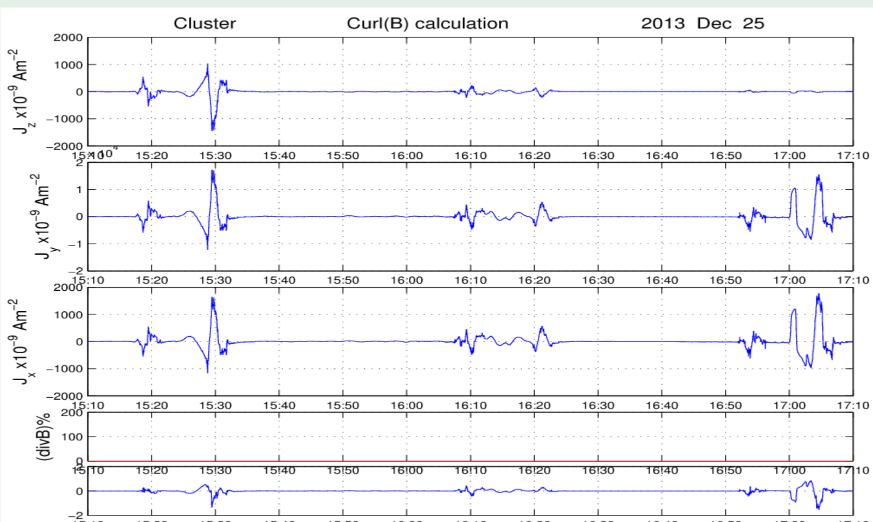


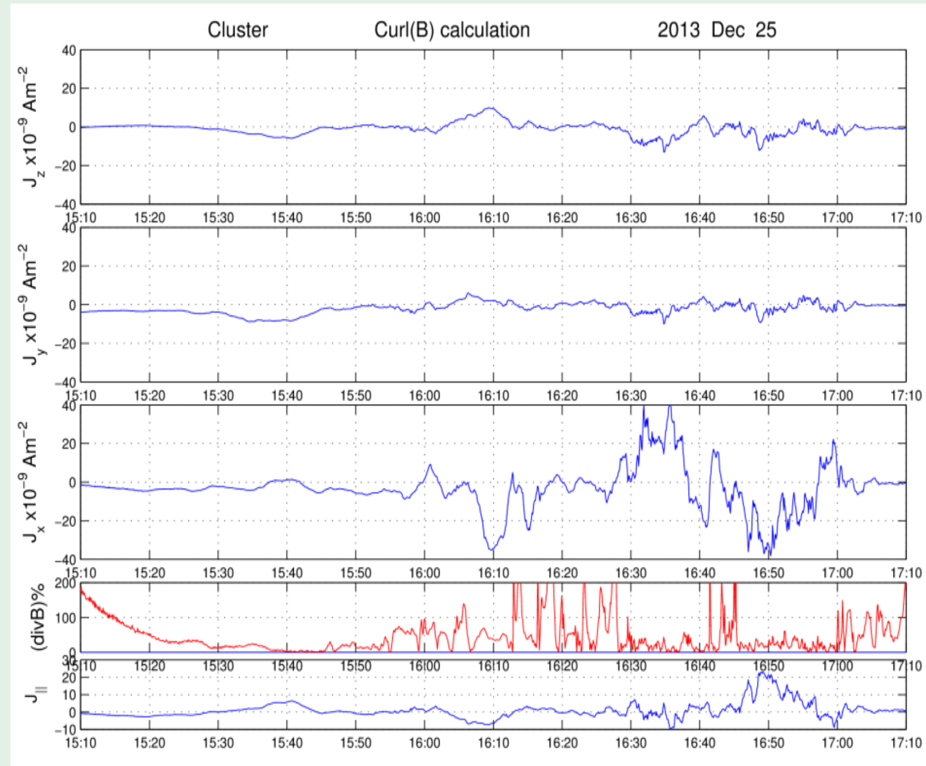
2013 Dec 25: Four spacecraft Cluster magnetic field data showing a clear J|| through cusp.
Also Cluster FAC signature is consistent with R2 connectivity (+/- 20 nAm^{-2}).

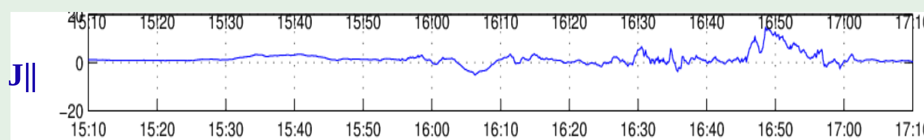
Cluster-Swarm Key configurations:











2013 Dec 25: Cluster enters FACs as Swarm reaches high latitude.

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Cluster-Swarm Key configurations: 2014

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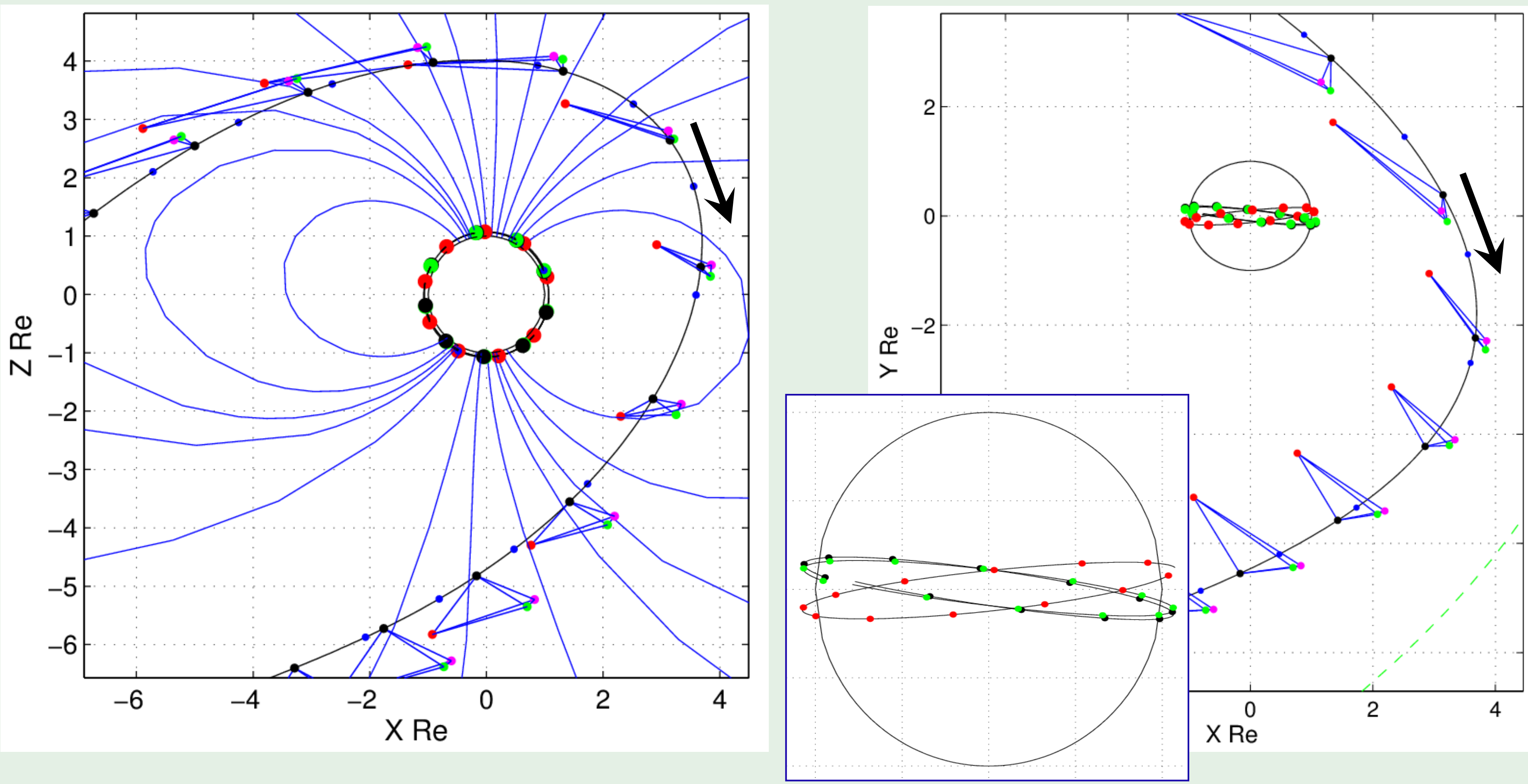
Accurately measuring curl(B) in FACs is difficult, due to the fine structure of the FACs.



2014 Sept 23: Close LT alignment during RC crossing.