The auroral generator: A case study using conjugated Cluster and FAST data

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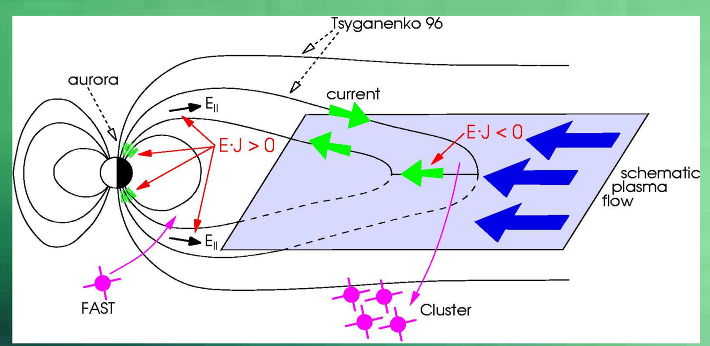
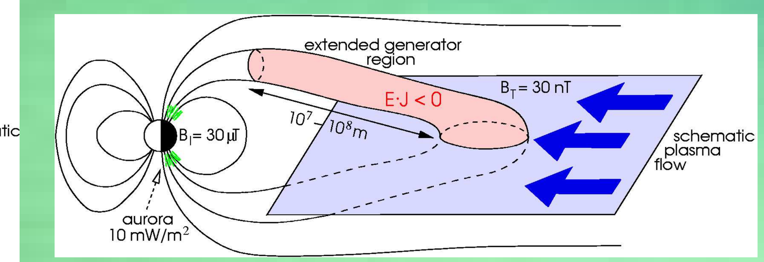
The auroral generator is a key constituent of the auroral current circuit. In the literature, however, there is a lack of detailed observational investigations of the generator and its properties. At present, Cluster provides a better platform for studies of the auroral generator, than previous single spacecraft missions. For example, the full current density vector can be derived from the simultaneous magnetic field measurements on the four spacecraft. In this paper we use conjugated data from the Cluster fleet (at an altitude of ~18RE) and the FAST satellite (at ~4000km) to investigate the auroral generator.

We examine the power density, E.J, as measured by Cluster, and present a nightside event where Cluster crosses a generator region, E.J<0. At the same time FAST detects precipitating accelerated electrons. To our knowledge, this is the first experimental evidence for the crossing of an auroral generator region. Our investigation is complicated by the fact that the electric field and current are close to the instrumental detection limit (the energy flux into the ionosphere requires quite small power densities in the generator region). However, a careful examination of the FAST data, of the mapping along the magnetic field line, and of the conjunction timing, contributes to the validation of the E.J<0 signature seen by Cluster.

Background

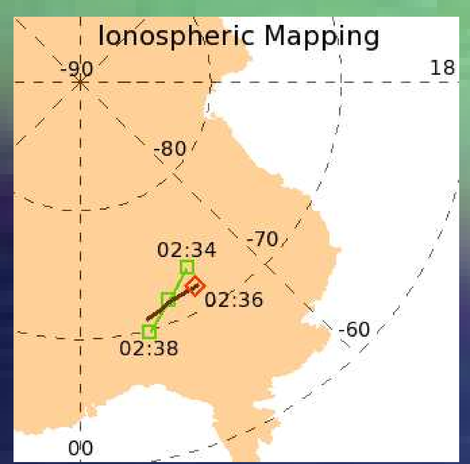


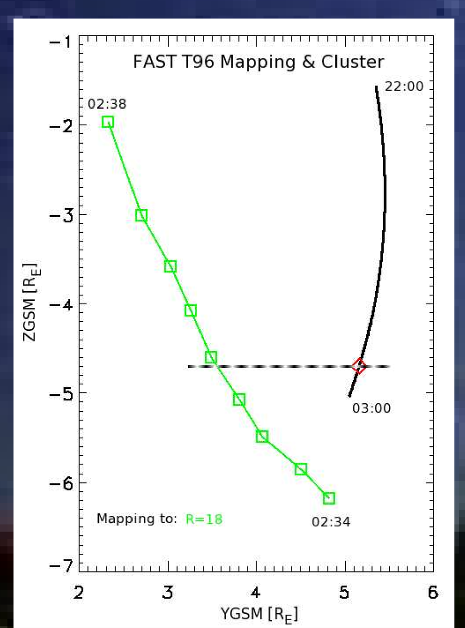
Schematic sketch of the auroral current circuit. The generator region (E.J<0) in the magnetosphere powers the loads in the acceleration region and the auroral ionosphere. Cluster is close to apogee, in the southern plasma sheet, while FAST passes below the acceleration region.



A moderately strong aurora (10mW/m ^{2}) maps to 10uW/m ^{2} in the tail. Assuming that the generator extends 1.5RE – 15RE along the magnetic field lines, an order of magnitude estimate of the power density in the generator region is 10^{-13}– 10^{-12} W/m^3 .

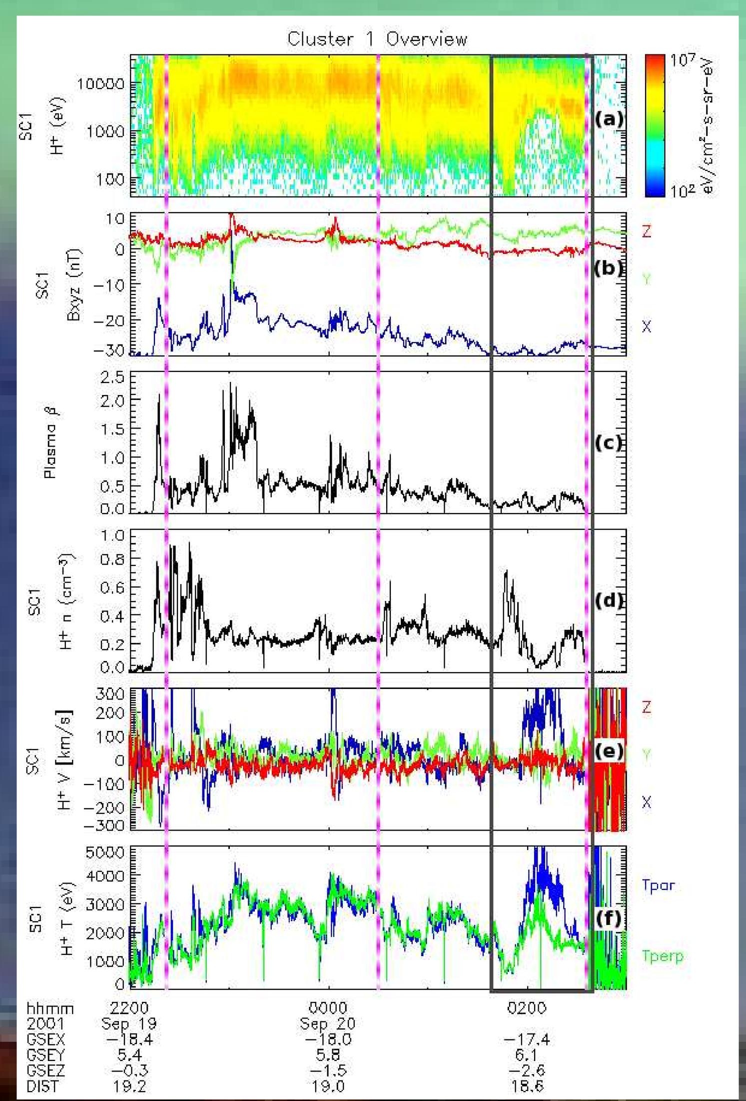
Conjunction





Ionospheric (top) and tail (bottom) projections of Cluster 1 (black + red) and FAST (green). For the mapping the T96 model is used. At the conjunction time, 02:36UT, the spacecraft are at the same magnetic latitude but separated in azimuthal direction. This separation is tolerable due to the azimuthal symmetry within the auroral oval.

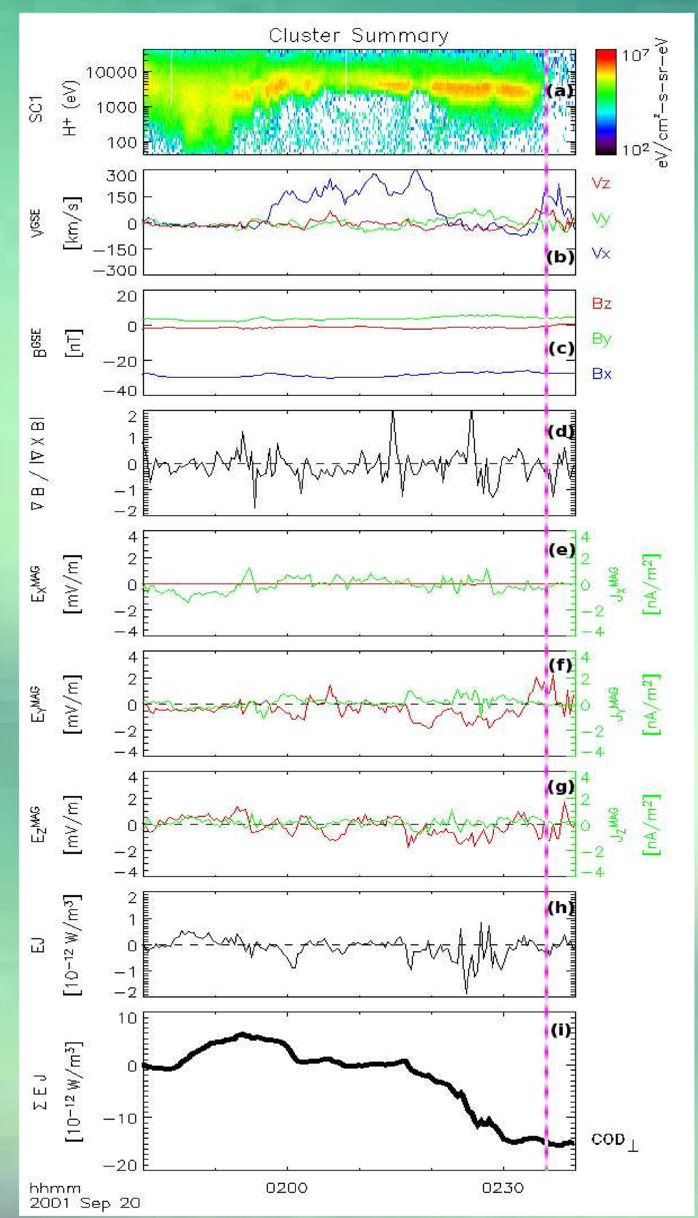
The choice of the reference system is important since E.J is not invariant under coordinate transformations. We use GSE. E.J should be calculated in the system of the loads. The power consumption E||.J|| in the acceleration region is invariant under (non–relativistic) transformations. The ionospheric load moves with the neutral wind velocity (<1km/s), which can be neglected.



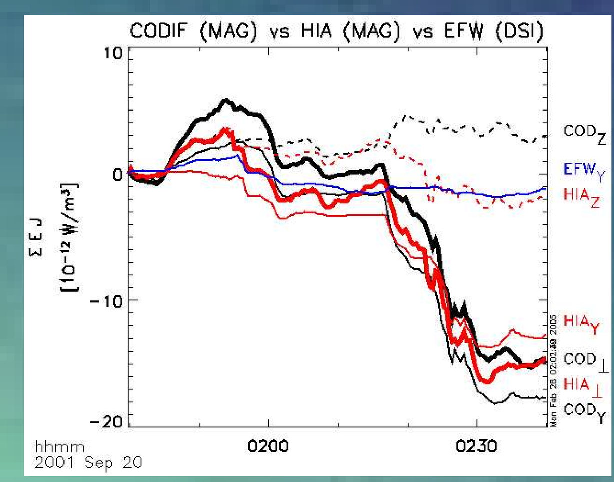
Overview of 5h of Cluster data containing 3 conjunctions. The rectangle shows the interval investigated here.

Cluster entered the northern plasma sheet on Sep. 19, ~12:45UT, and crossed the neutral sheet ~16:00. Because of the plasma sheet motion, the spacecraft made an excursion to the southern lobe from 20:45 to 22:15, then returned to the plasma sheet until ~02:36. The spacecraft are below the neutral sheet (c.f. Bx) and close to the lobe boundary (c.f. plasma beta). The velocity is mostly <100km/s, but there are ~300km/s peaks in Vx near both ends of the plasma sheet and also inside it. The temperature is mostly isotropic with typical plasma sheet values, 1–4keV, except for 02:10–02:36.

Cluster data

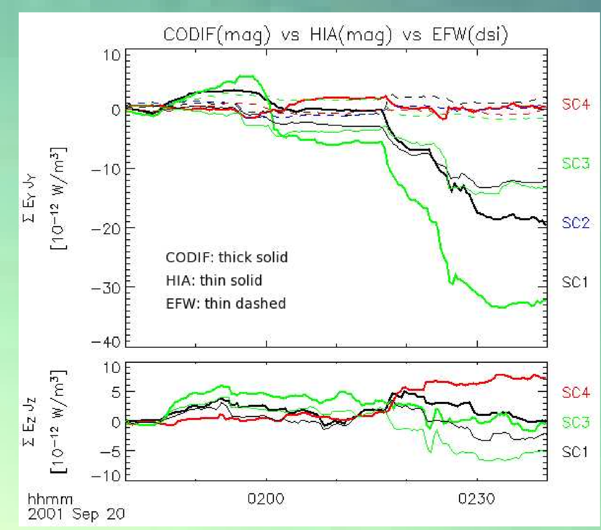


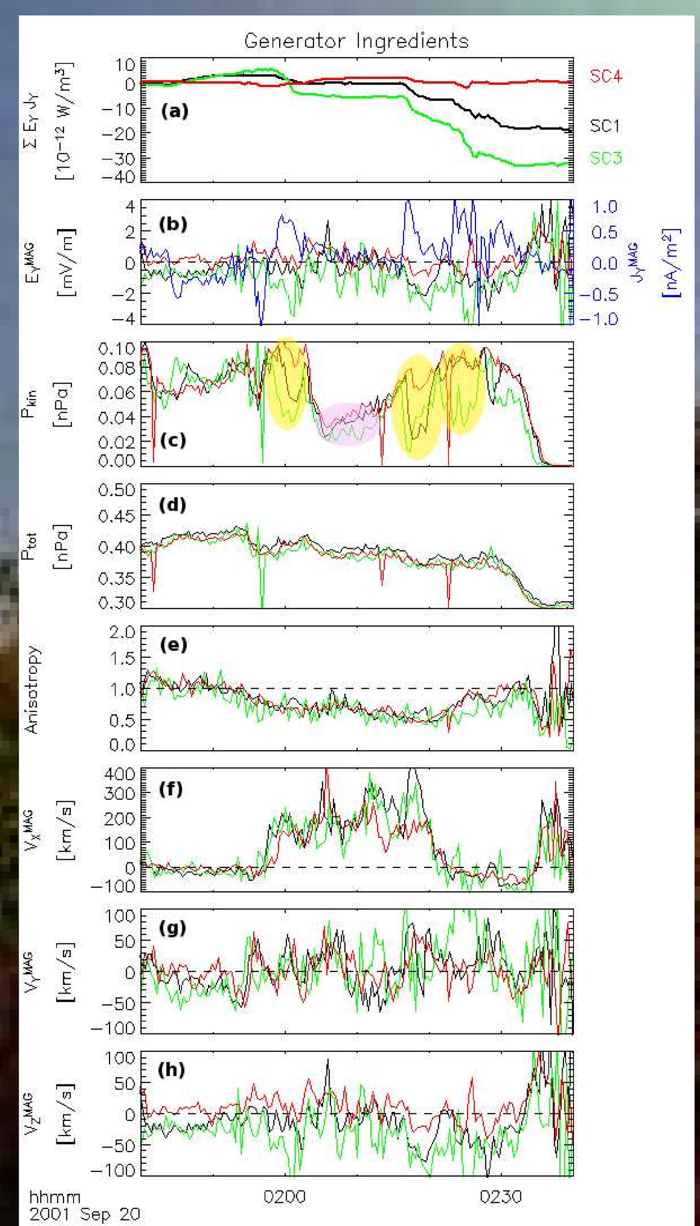
Summary of the Cluster data (left). The electric field and current density are expressed in a magnetic field aligned system (MAG) which is close to GSE. The FAST conjunction is indicated by the vertical magenta line. The bottom panel shows a clear drop in the cumulative sum of E.J, indicating a Concentrated Generator Region (CGR).t



Zoom on the cumulative sum of E.J (top right), corresponding to CODIF (black), HIA (red) and EFW (blue) electric field data. Thick lines show the total, thin solid/dashed lines show contributions from Y/Z in the MAG system. Only EFW Y data is presented (in the DSI system which is close to GSE). Most of the generator signatures comes from the Y direction.

Both CODIF and HIA agree on E.J<0, but not EFW (note that ASPOC is off on s/c 1 and 2). Cumulative sum of E.J (bottom right) corresponding to electric fields from all available instruments and spacecraft. The main contribution to E.J<0 comes from CODIF–Y and HIA–Y on SC1 and SC3.





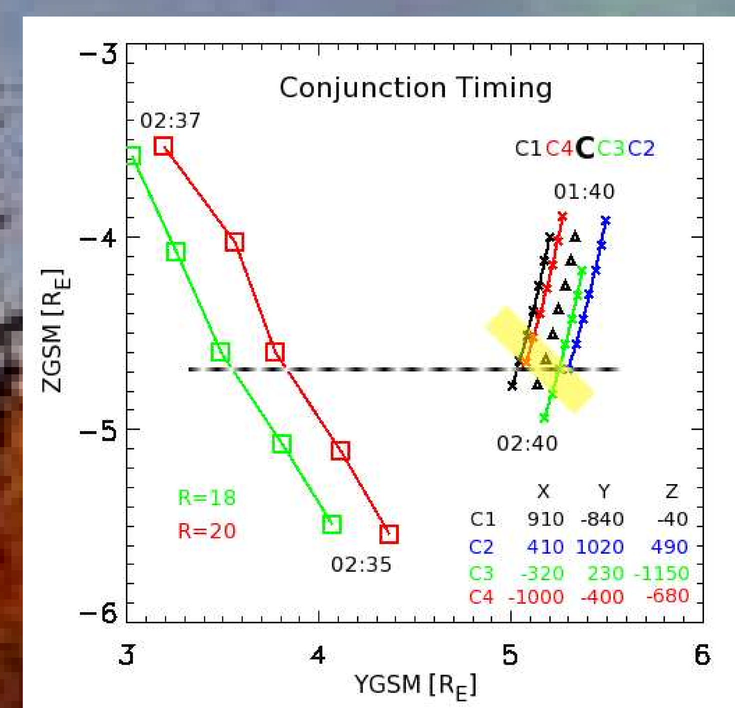
The generator ingredients (left). The yellow shading in (c) indicates intervals with large gradients in the kinetic (thermal) pressure, while the magenta shading in between shows almost no gradients. The total pressure (d) is almost constant. This suggests a complicated 3D wavy structure of the plasma sheet boundary (PSB). Vz<0 and Vy>0 (g, h) on SC1 and SC3, close to the PSB, support this interpretation.

Tail footprint of FAST and projections of Cluster spacecraft (right). The conjunction is indicated with the horizontal black line. The shaded area shows roughly the CGR projection near Cluster. The detection of the generator signature just on SC1 and SC3 suggests that the CGR varies both in space and in time. We estimate a CGR extension along the field line of up to a few 1000km.

By examination of the Poynting theorem,

$$\mathrm{div}S = -\delta P_B / \delta t - E.J \qquad (1)$$

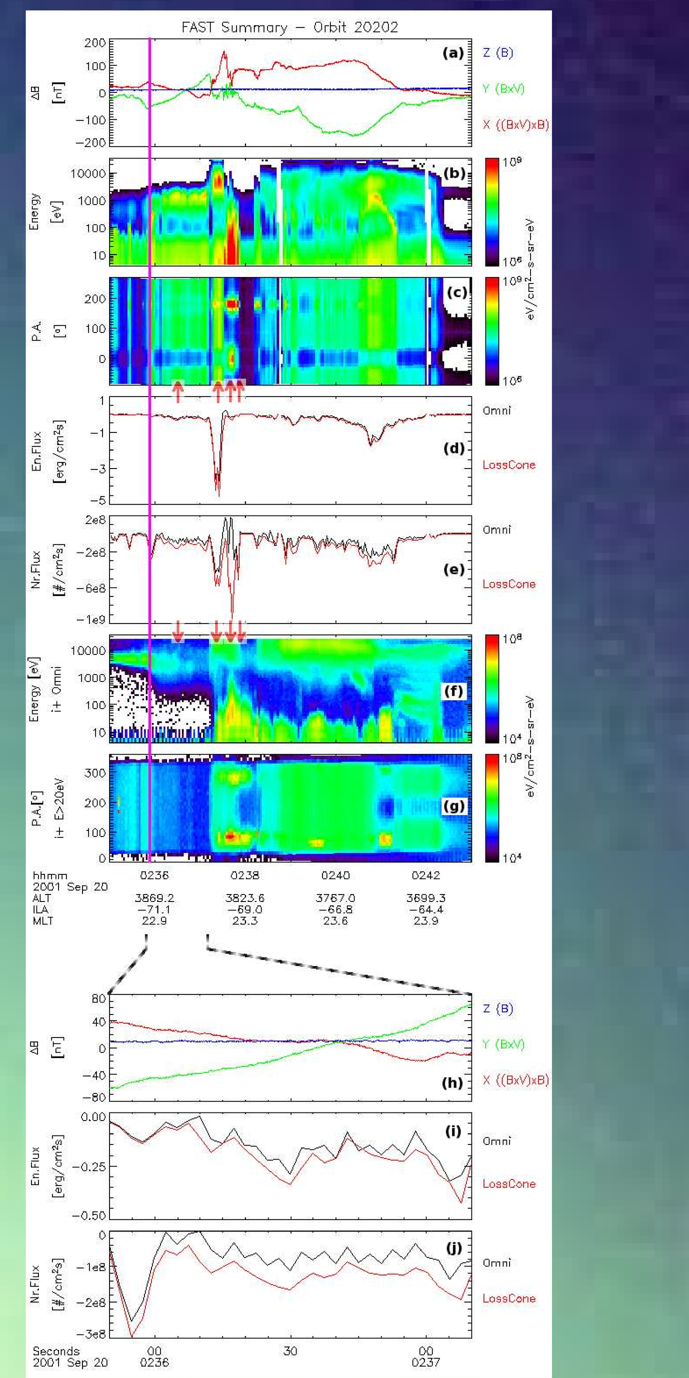
one obtains that when E.J<0, a sufficient condition to get divS>0 is $\delta P_B / \delta t<0$. In panel (c) it is seen that during the CGR there are times when $\delta P_B / \delta t$ decreases. At those times there is a net Poynting flux leaving the CGR, that could contribute to the energy dumped in the auroral ionosphere near the polar cap boundary.

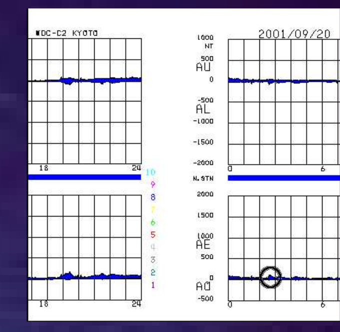


	X	Y	Z
C1	910	-840	-40
C2	410	1020	490
C3	-320	230	-1150
C4	-1000	-400	-680

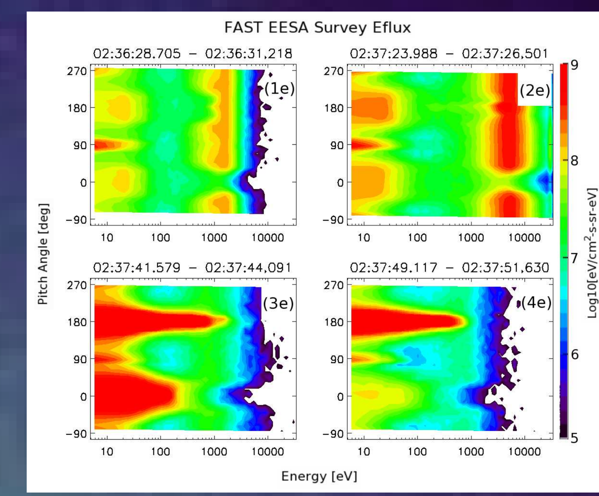
Acknowledgement:
We are pleased to thank Adrian Blagau, Mehdi Bouhram, Tomas Karlsson, Yuri Khotyaintsev, Göran Marklund, Götz Paschmann, Kjell Rönnmark, and Hans Vaith for fruitful discussions. The background auroral picture, courtesy Jan Curtis. The work in Germany was supported by the Zentrum für Luft– und Raumfahrt under contract 50 OC 0102. The work in Romania was funded through the program AEROSPATIAL, contracts 72/2003 PROSPERO and 118/2004 DIAFAN.

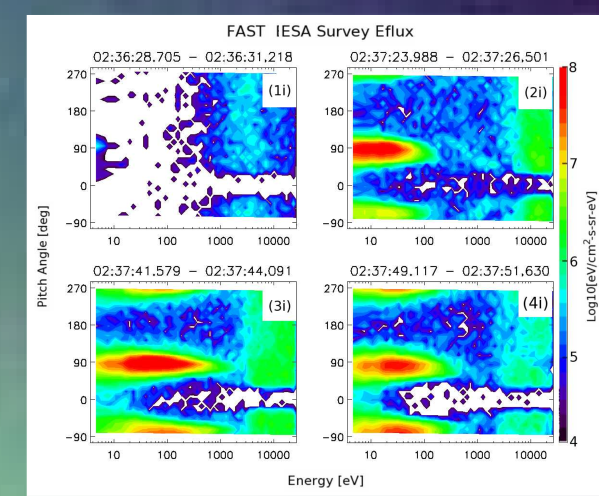
FAST data





Auroral activity indices (WDC, Kyoto). The circle indicates a bump in AE near the conjunction time, possibly the onset of a small substorm. The magnetospheric activity is low (Kp~1).





Top: FAST summary plot. There is evidence for auroral activity after the conjunction time. The dramatic change at 02:37:10 suggests that FAST captures the onset of a small substorm. In the Cluster data, the generator is seen a few minutes before the (head–on) conjunction. Bottom: Zoom on the magnetic field perturbation, energy flux, and number flux The data are consistent with a current sheet almost parallel (within ~15deg) to the E–W direction. The electrons carry a net downward energy flux of ~0.25mW/m ^{2}(~1mW/m ^{2} when mapped to the ionosphere).

Electron (top) and ion (bottom) distributions at the times of the arrows in the FAST summary plot (left). Distributions (1e,i) are typical for a quiet interval: Accelerated ~1.5keV electrons (rather isotropic outside the loss–cone) together with loss–cone plasma sheet ions. The distributions (2,3,4) are collected during the active interval 02:37:10–02:37:50. Heated conter–streaming electrons and transversely accelerated ions are visible. The asymmetry between 90 and 270deg (2i) is due to the ram velocity of the dominant oxygen.

Conlusions

To our knowledge this is the first observational investigation of the power density, E.J, in auroral generator regions. The order of magnitude estimate of E.J is consistent with J and E measurements close to the detection limits of the Cluster instruments. One cannot expect accurate values of E.J, but the sign and general trends are easier to obtain. To increase the reliability of E.J, we use data from three different electric field instruments on Cluster.

The Cluster data were collected within the plasma sheet boundary layer (PSBL). Even at quiet times, the PSBL is an active location: Electric fields are associated with plasma motion, caused by the dynamics of the plasma–sheet / lobe interface, while electrical currents are induced by pressure gradients. We show that these ingredients do indeed sustain the conversion of mechanical into electromagnetical energy, as proved by E.J<0. An examination of the conjugated FAST data and the conjunction timing contributes to the validation of the generator signatures seen by Cluster.

The plasma characteristics in the vicinity of the generator regions indicate a complicated 3D wavy structure of the PSB. Consistent with this, we suggest that at least part of the generated electromagnetical energy is carried away by Alfven waves, to be dissipated in the auroral ionosphere, near the polar cap boundary.