

LA PHYSIQUE AURORALE ET SES MYSTERES

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**Atelier PNST/SHM
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Zones aurorales

Terre

Perte d'ions O^+ (3 kg s^{-1})

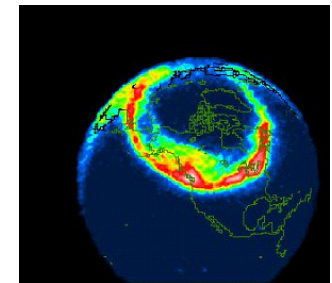
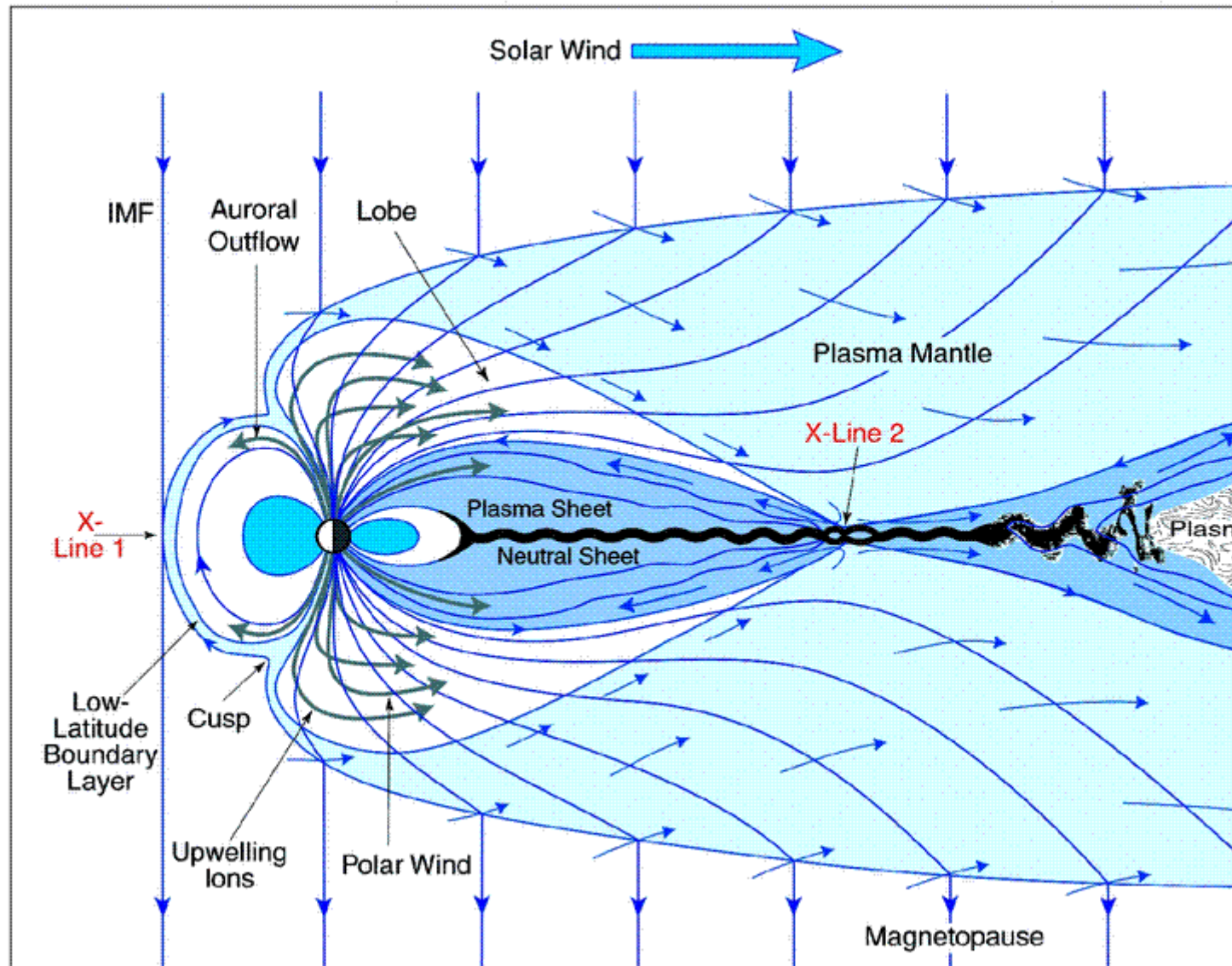
Vent solaire

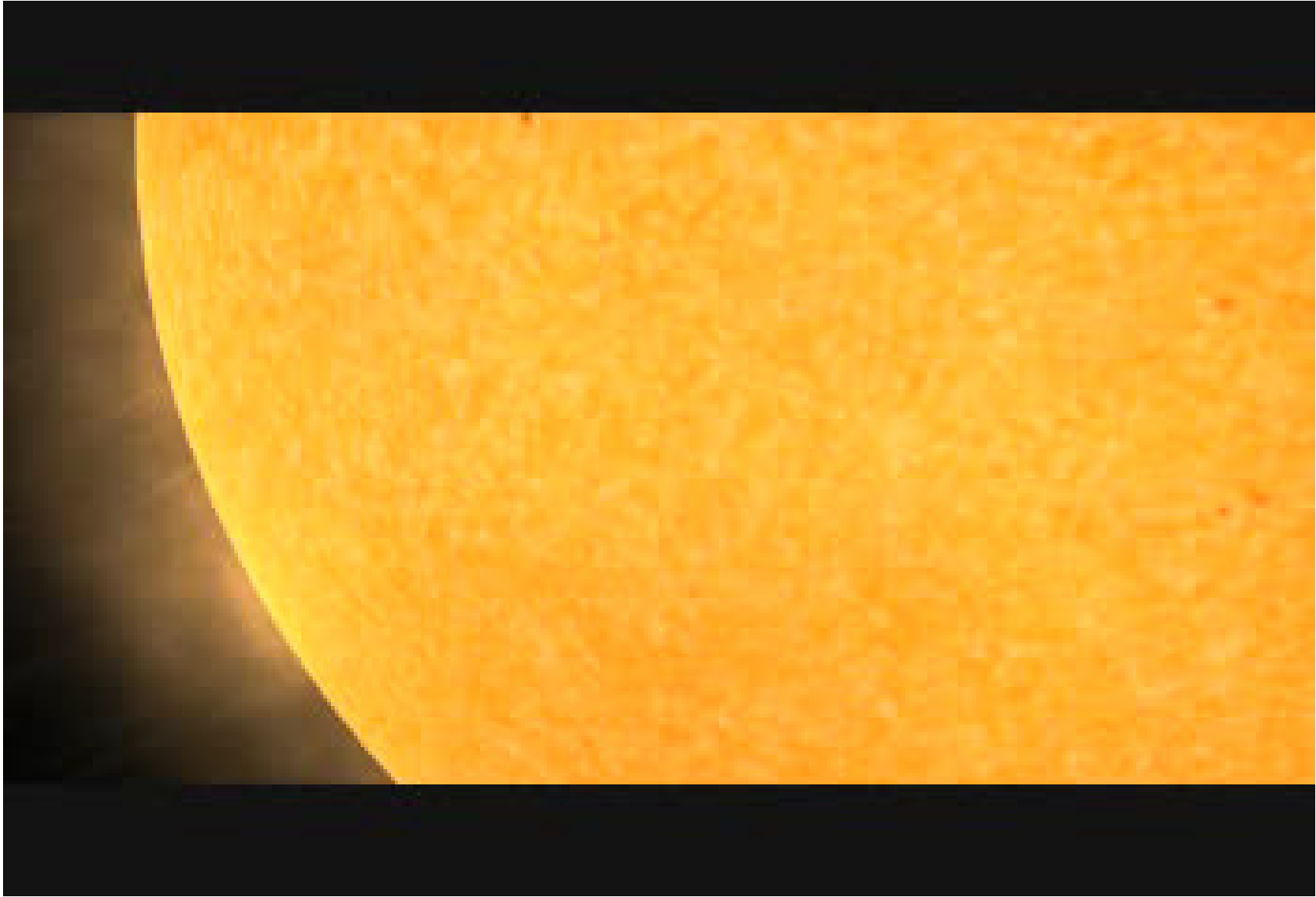
Accélération électrons (10 keV)
Aurores

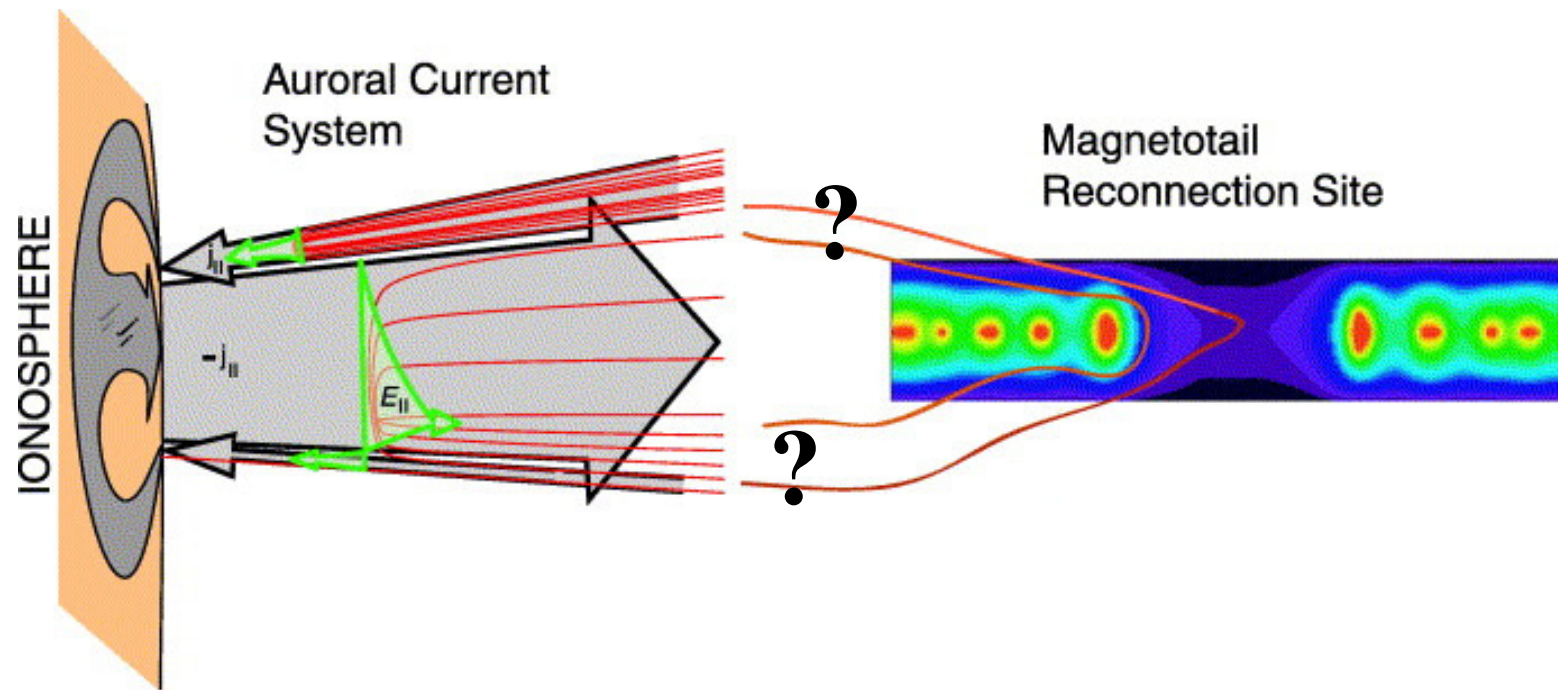
Rayonnement kilométrique
(10^9 W)



Reconnection processes in the tail of the magnetosphere provide the primary energy source for aurora during substorm:





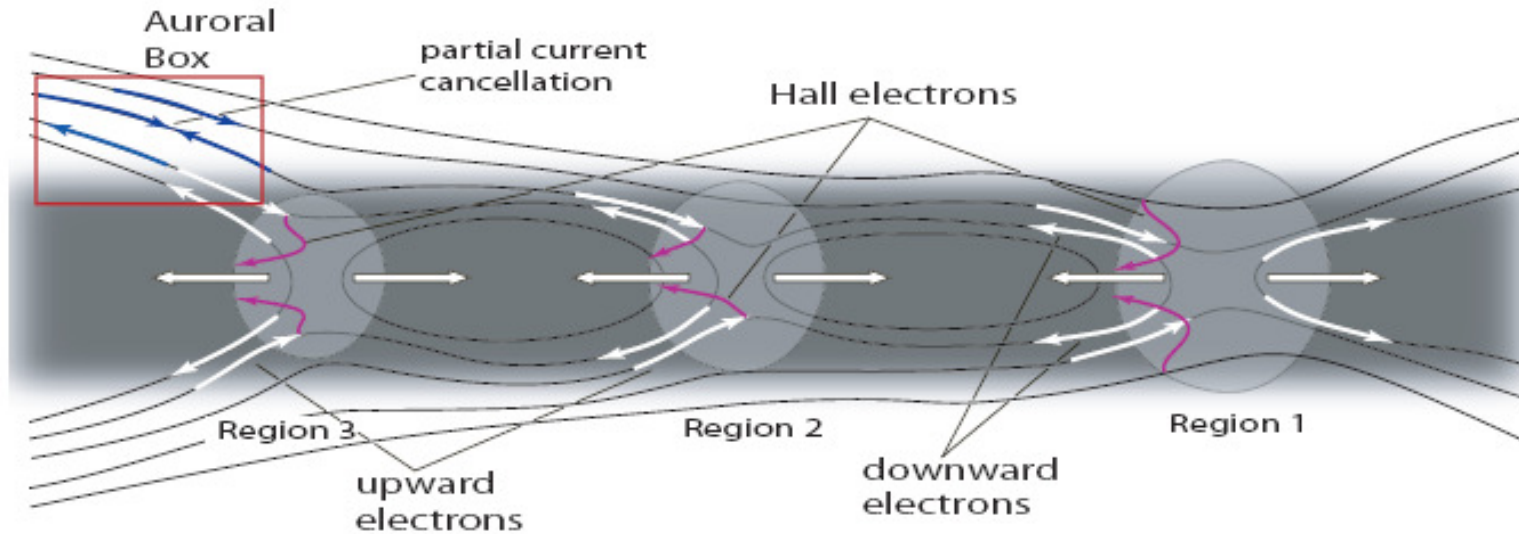


How does the system evolve from Alfvénic aurora at the onset of a substorm to a quasi-static particle acceleration through potential drops?

Reconnection during substorms may be of statistical nature, consisting of many small reconnection sites.

The acceleration of electrons takes place in a primary step followed by a sequence of several secondary acceleration steps.

SKETCH OF MULTI-ADJACENT RECONNECTION SITES



- The reconnection sites form a chain of X-points and islands which are in mutual motion and interact with each other
- Strong reconnection in one place may suppress weak reconnection in another place

Les électrons en provenance de la surface externe de la magnétosphère sont accélérés vers la Terre (~10 keV)

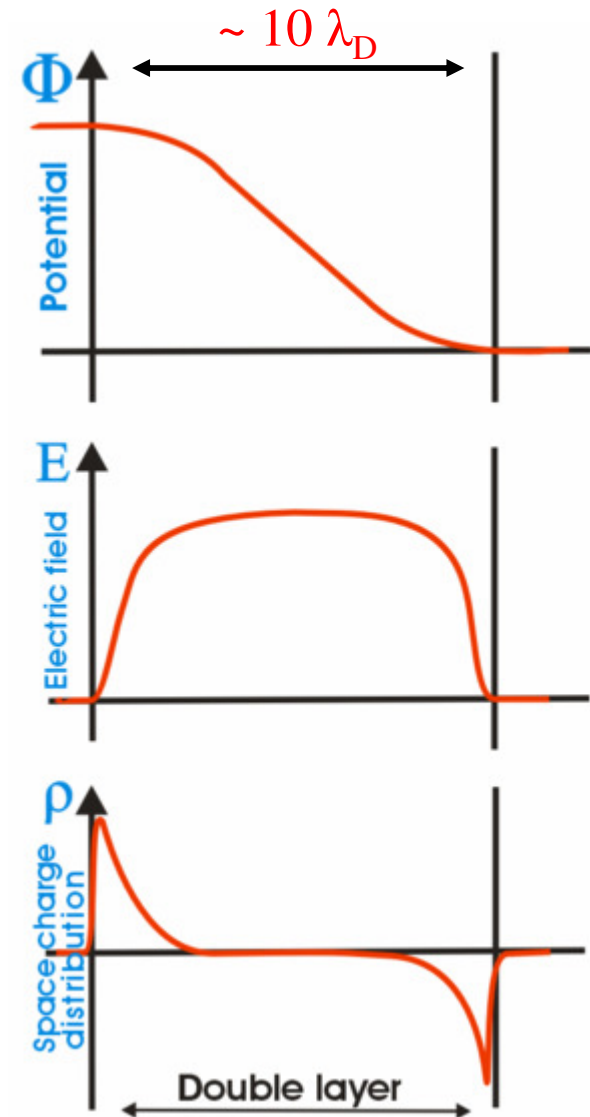
PROBLEME: La conductivité le long des lignes du champ magnétique est infinie: le champ électrique parallèle devrait être nul!

REPONSE: Les mesures à haute résolution temporelle montrent que la turbulence atteint un niveau d'amplitude élevé et s'organise en structures de petites échelles (double couches, structures solitaires....)

Champs électriques parallèles supportés par des structures non linéaires localisées engendrées par interactions ondes-particules

DOUBLE LAYERS / ELECTROSTATIC SHOCKS

- ◆ Structures in a plasma consisting of two parallel layers with opposite electrical charge,
- ◆ The electrostatic structures are very thin (Typically 10 Debye lengths),
- ◆ They can sustain a local region of parallel electric field,
- ◆ First advocated by Alfvén (1958) in astrophysical context,
- ◆ **Radiation from DL may explain observed intense and narrow band bursts from stellar and planetary magnetospheres.**



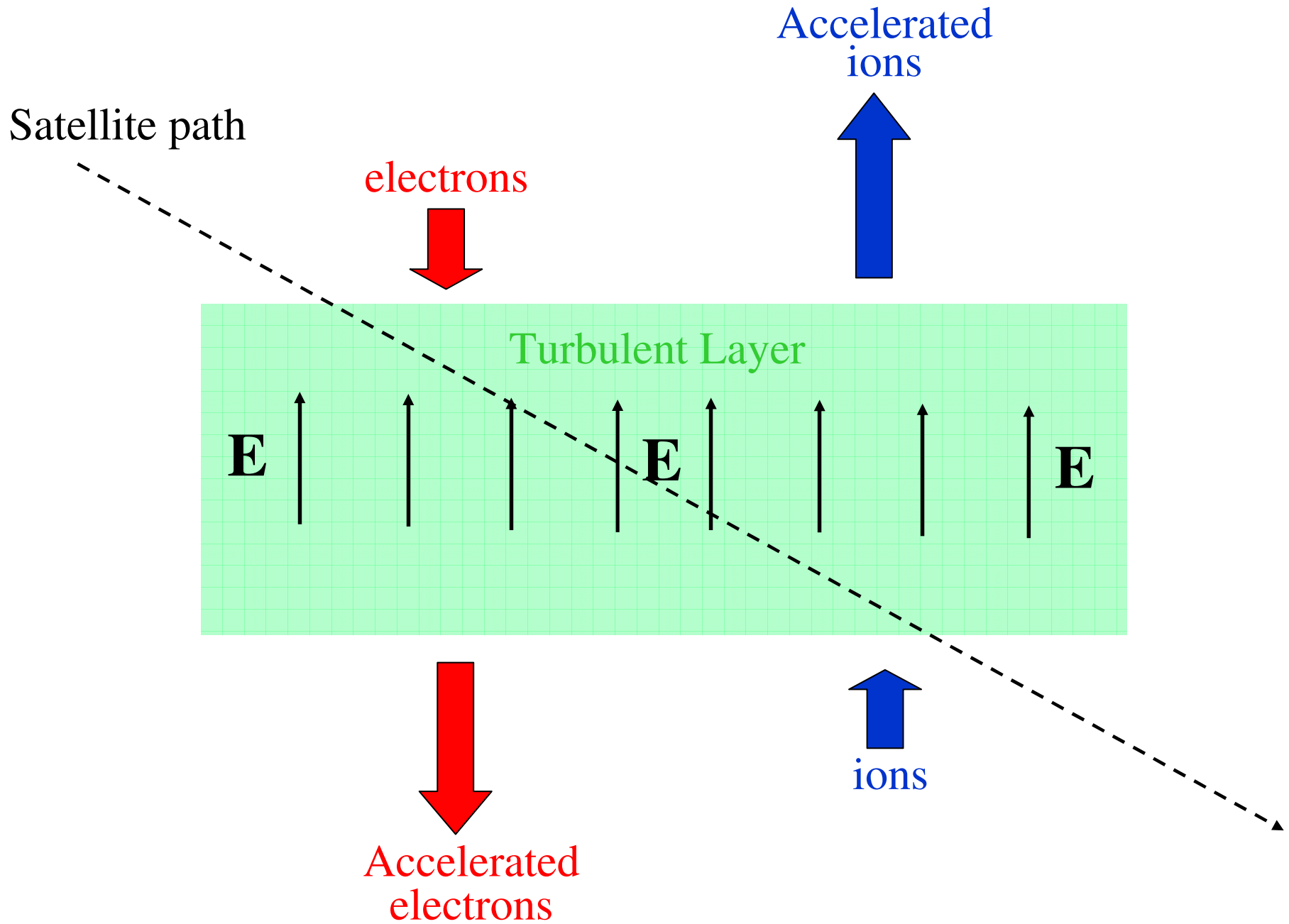
ELECTRIC POTENTIAL DROP ACROSS A DL

Energy Conservation Law: $|j_{//}E_{//}| \approx d(nk_B T_e)/dt$

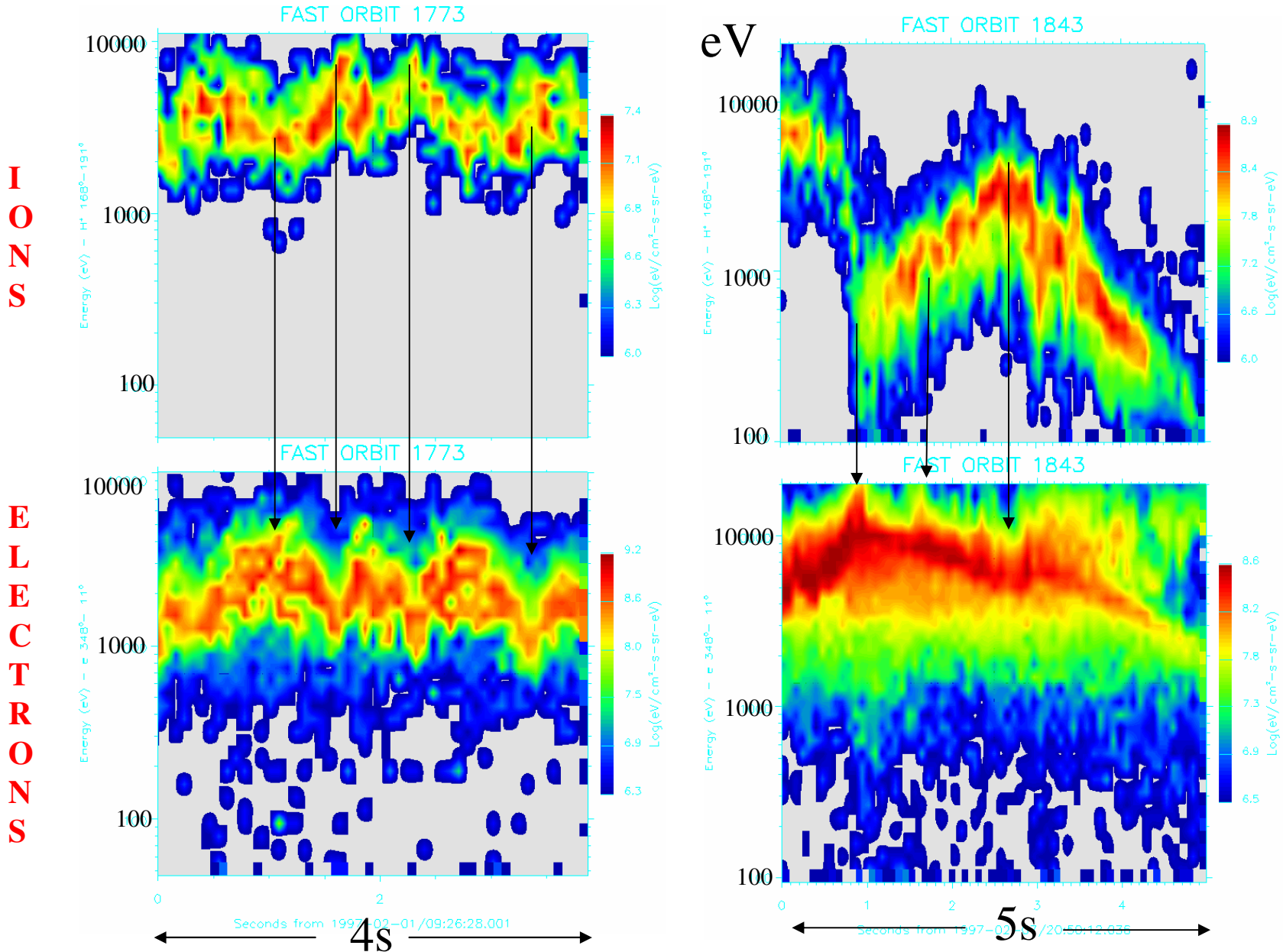
For a quasi-stationary double-layer causing a density depression Δn by evacuating the plasma in a region of length Δx while moving at speed v_s , the potential drop $\Delta\Phi = E_{//} \Delta x$ can be approximated by:

$$\Delta\Phi \approx \frac{\Delta n}{n} \frac{n}{n_b} \frac{v_s}{v_b} \left(\frac{k_B T_e}{e} \right)$$

Assuming a nearly complete evacuation of the plasma $\Delta n \sim n$, the **potential difference can reach several kV ($e\Phi \geq k_B T_e$) in the auroral magnetosphere.**



ELECTRON-ION ANTI-CORRELATION PARALLEL ENERGIES

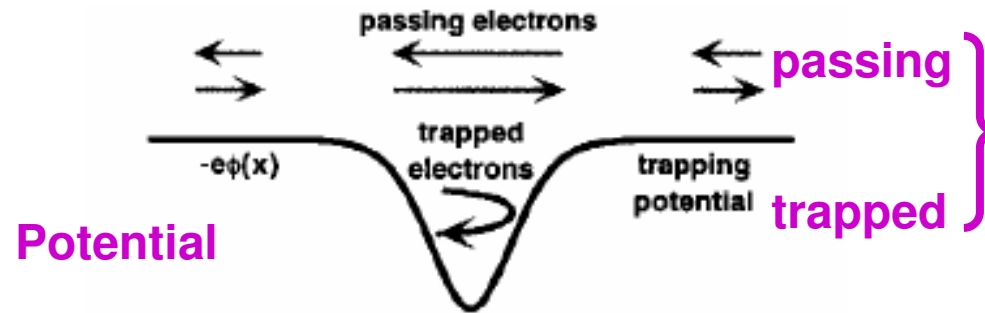


Turbulence:

Trous dans l'espace des Phases

- **Structures non linéaires -localisées à l'échelle de la longueur de Debye – qui sont associées à une population de particules piégées;**
- **Formation des trous dans l'espace des phases se produit durant la phase non linéaire d'une instabilité (Buneman, Double faisceau...);**
- **Quand les ondes de plasma atteignent de grandes amplitudes elles peuvent piéger un nombre important de particules du plasma ambiant.**

Hole Formation Mechanism



Phase space distribution

Potential

Field



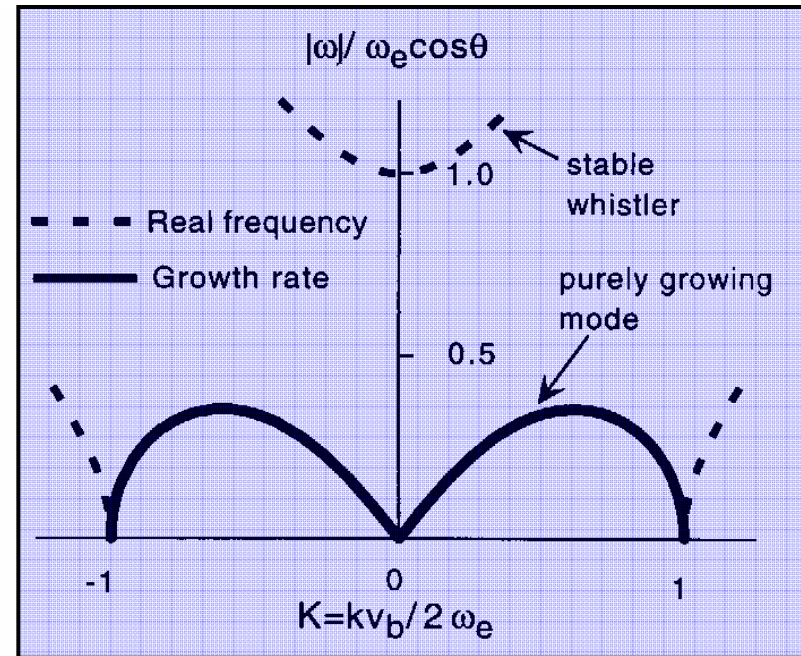
Density



Hole

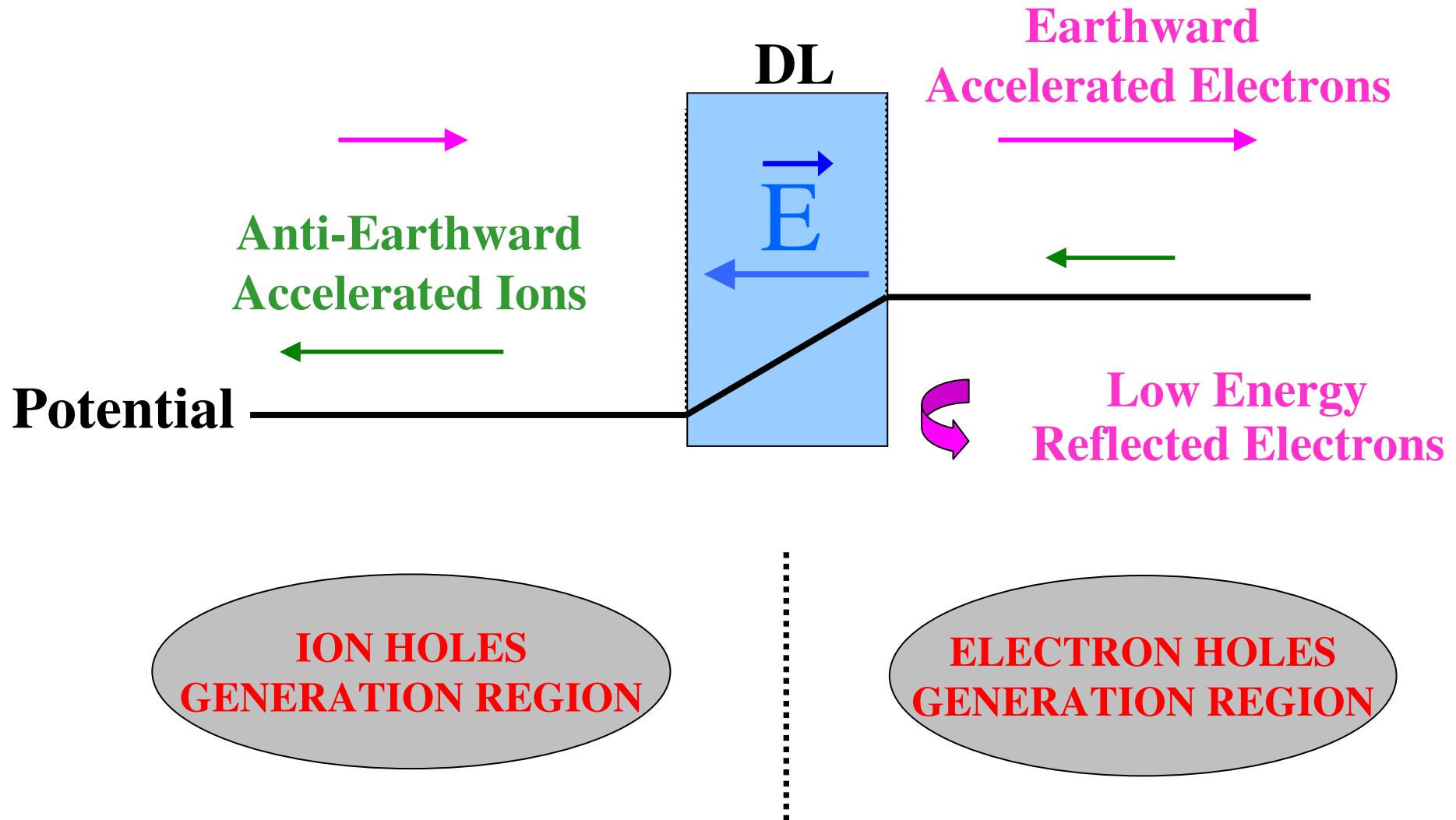
Real space distance

Two-stream instability



(after Goldman et al. 1999, NPG)

Localized DL in the acceleration region



Les « Double Couches » (chocs) engendrent des «trous» dans l'espace des phases:

Dans les régions de potentiel élevé:

Des trous d'électrons de faibles amplitudes se propagent à grande vitesse (~1000 km/s);

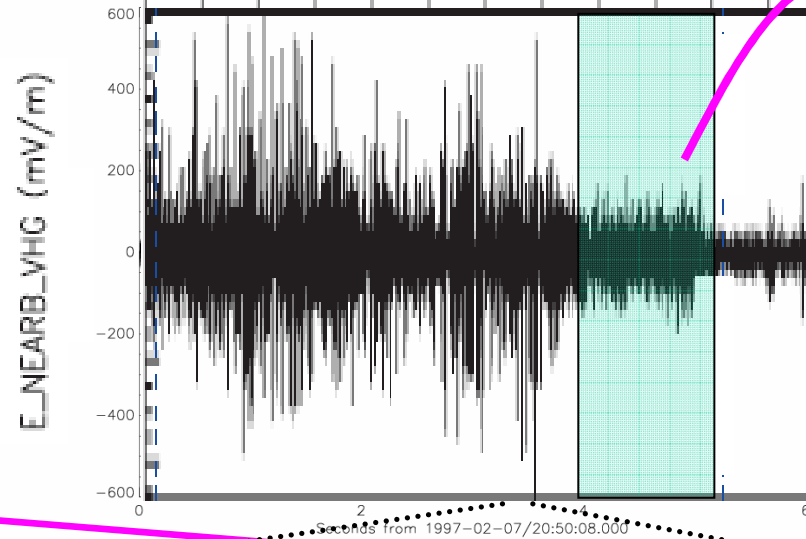
Dans les régions de faible potentiel:

Les trous d'ions réfléchissent les électrons de faibles énergies;

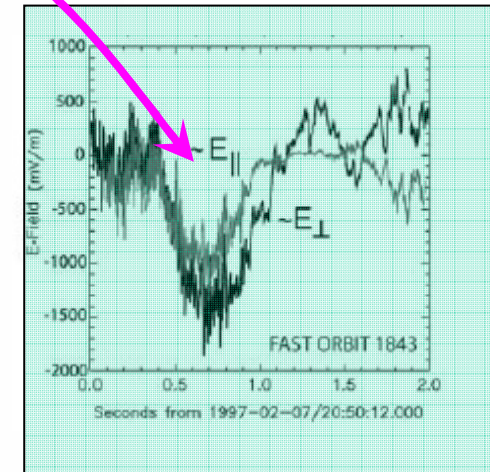
Chaîne de trous d'ions et d'électrons de grandes amplitudes est ainsi créée, ces structures se propagent à la vitesse de dérive des faisceaux d'ions (~100 km/s);

LOW POTENTIAL SIDE OF A DL: TRIPOLAR ELECTRIC FIELD STRUCTURES

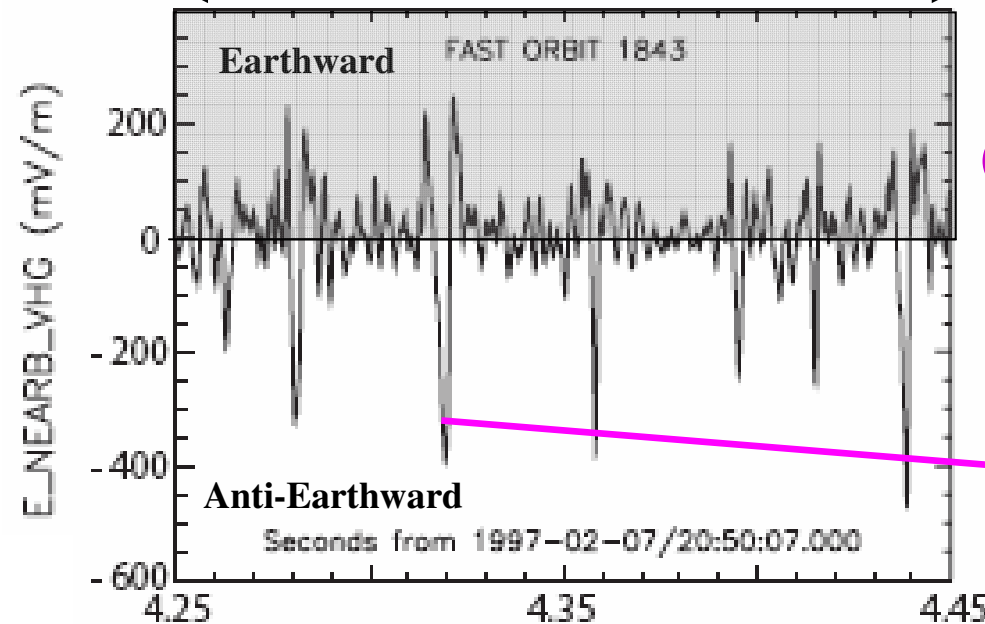
Electric Waveform



Double Layer



200 ms

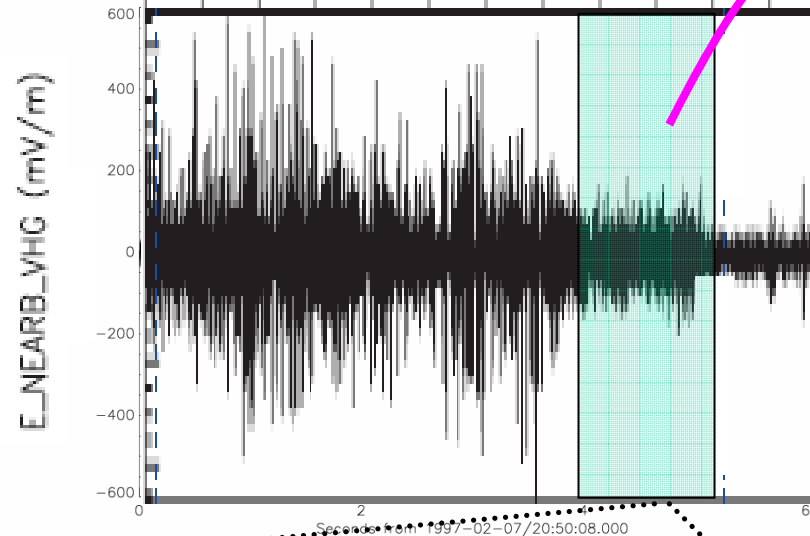


$|\Delta E| \sim 1000 \text{ mV/m}$

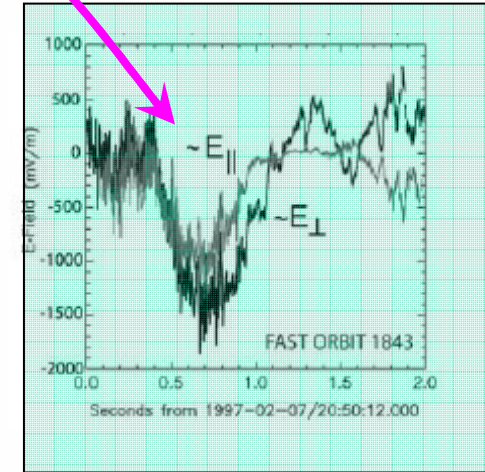
$\sim 5 \text{ ms}$

HIGH POTENTIAL SIDE OF A DL: BIPOLAR ELECTRIC FIELD STRUCTURES

Electric Waveform



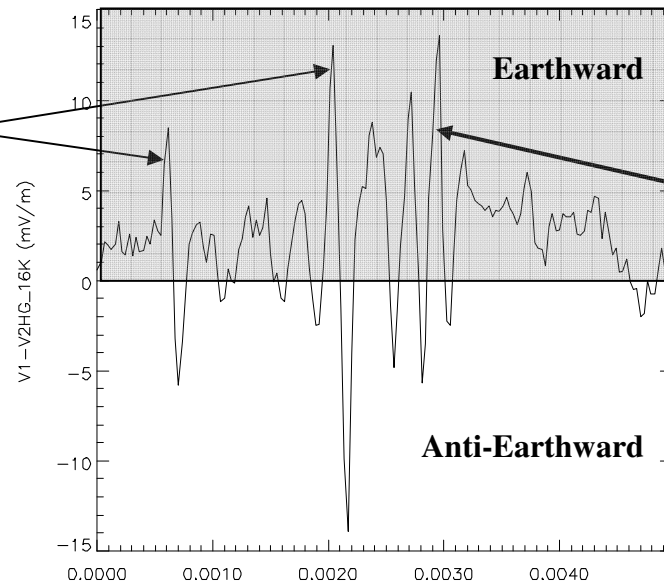
Double Layer



Seconds from 1997-02-07/20:50:08.000
FAST ORBIT 1843

Electron Holes

$|\Delta E| \sim 10 \text{ mV/m}$
 $\Delta t \sim 200 \mu\text{s}$



Electron Acoustic Waves

5 ms

TURBULENCE DANS LES REGIONS D'ACCELERATION AURORALES:

Une grande partie de l'accélération est produite au travers de structures turbulentes localisées (~ 10 km):

- **Supportant un champ électrique aligné avec le champ magnétique terrestre qui accélère les ions et les électrons dans des directions anti-parallèles,**

- **Le potentiel des double couches est de plusieurs kV,**

Des “trous d'ions et d'électrons” (~1km) sont engendrés au voisinage des double couches:

- **Présence de structures multipolaires non linéaires cohérentes: Responsables de la génération des structures fines du Rayonnement Kilométrique Terrestre ?**

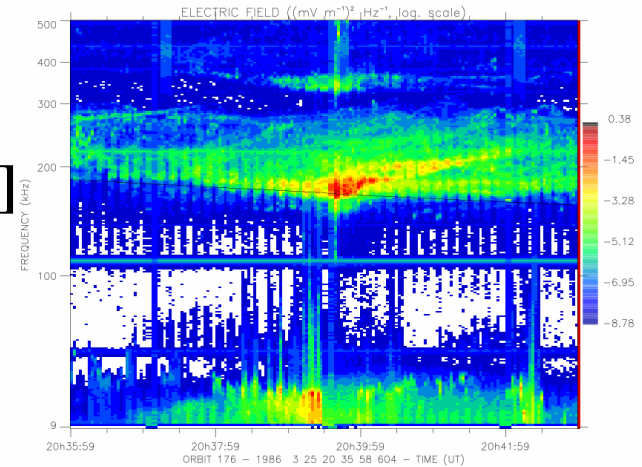
RAYONNEMENT KILOMETRIQUE AURORAL

RKA est un puissant rayonnement électromagnétique non thermique:

Observé par les satellites “Elektron” [1965]

Gamme de fréquence : 30-700 kHz

Puissance total ~ 10^7 W- 10^9 W.

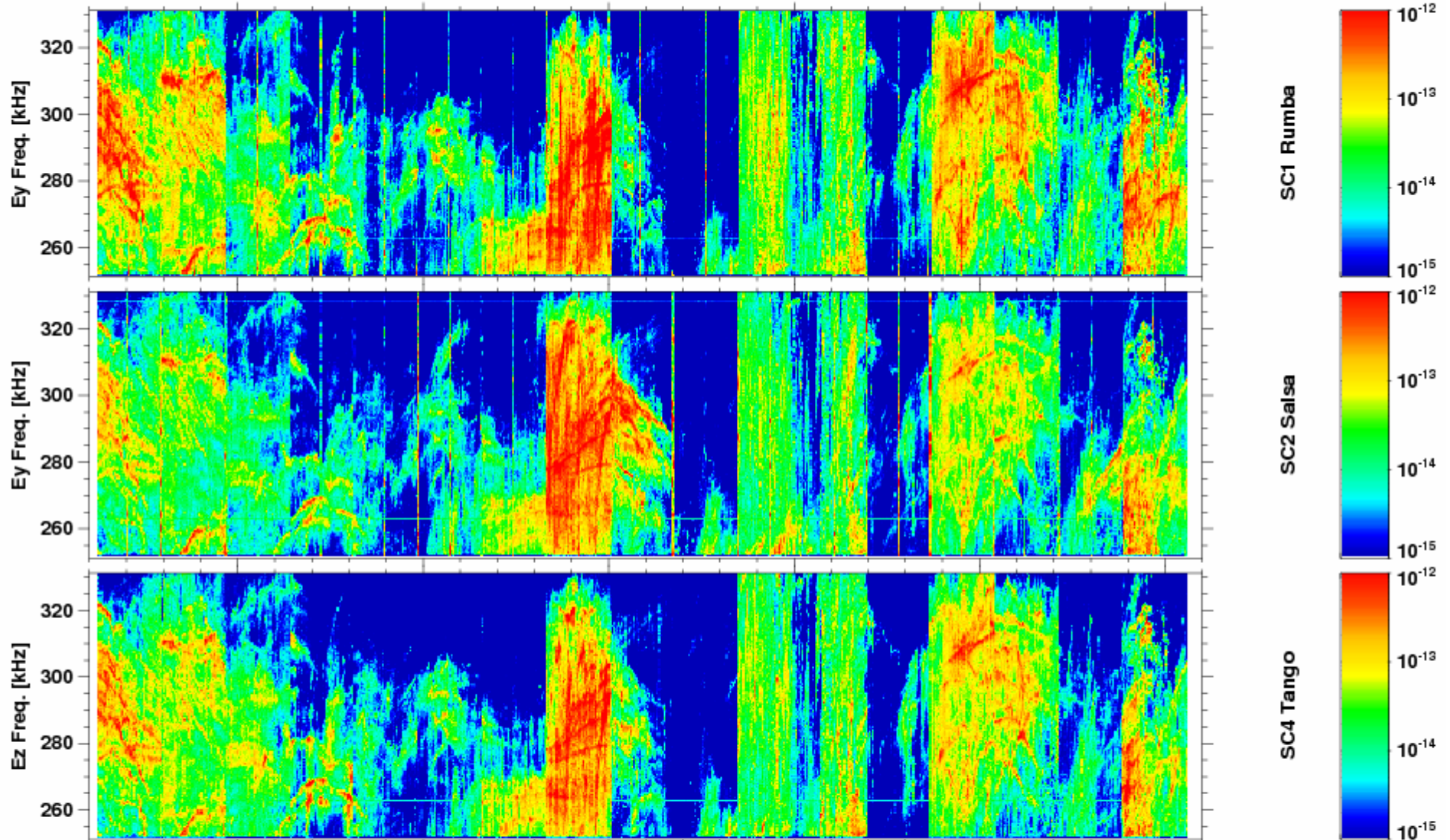


Conversion efficace de l'énergie des électrons ~ 1%.

Cluster WBD 77 kHz

FFT Size 1024 (Overlap 0)

$V^2 m^{-2} Hz^{-1}$



	09:00	09:10	09:20	09:30	09:40	09:50
R_E	9.38	9.16	8.93	8.71	8.47	8.24
MLAT	-74.61	-74.27	-73.85	-73.36	-72.78	-72.12
MLT	11.91	11.64	11.37	11.11	10.86	10.62

CYCLOTRON MASER INSTABILITY

Relativistic wave-particle resonance condition [Wu and Lee, 1979]:

$$\omega = \Omega_e \sqrt{1 - \frac{v^2}{c^2}} - k_{//} v_{//} \quad \frac{\omega_p}{\Omega_e} \ll \frac{v}{c}$$

Resonant circle centered at $v_{//} = -k_{//} c^2 / \Omega_e$:

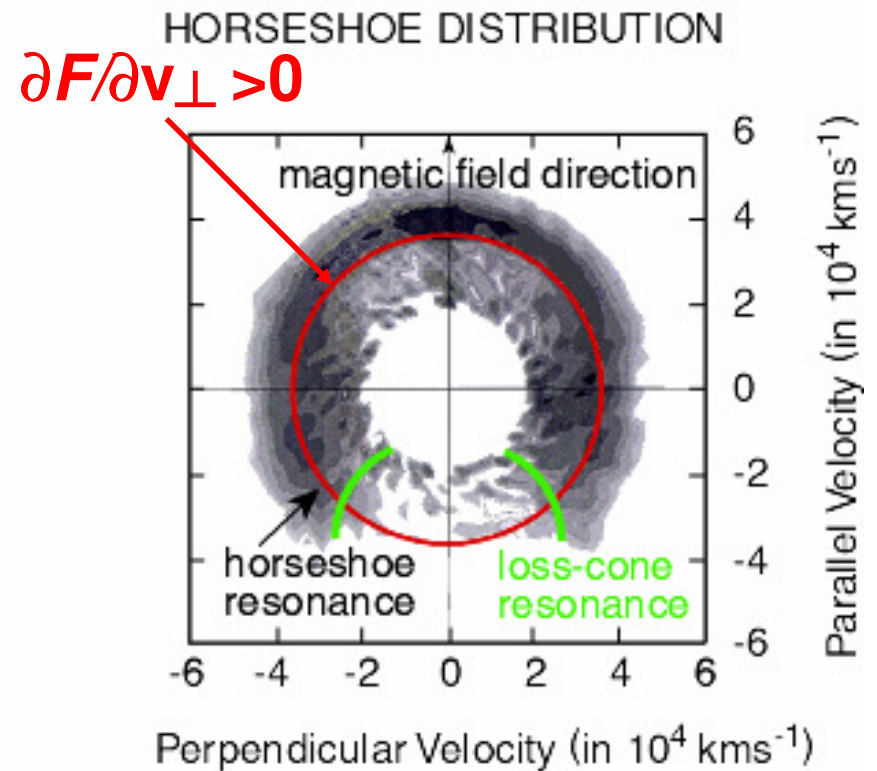
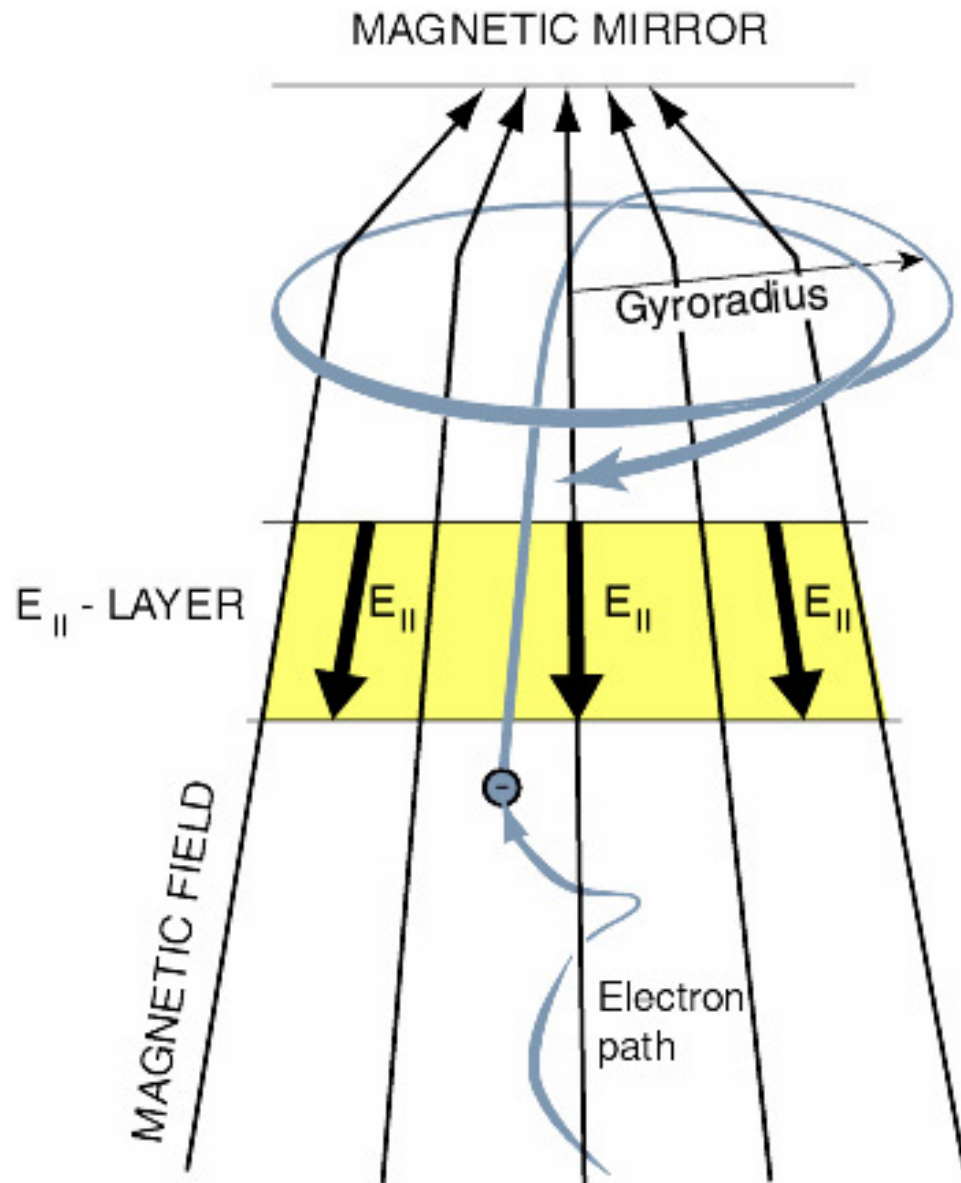
$$\omega = \Omega_e \left(1 - \frac{v^2}{2c^2} \right) c^2 + \frac{k_{//}^2 c^2}{2\Omega_e}$$

For $k_{//} = 0$ Emission at $\omega < \Omega_e$

Resonant circle centered at $v_{//} = 0; v_{\perp} = 0$

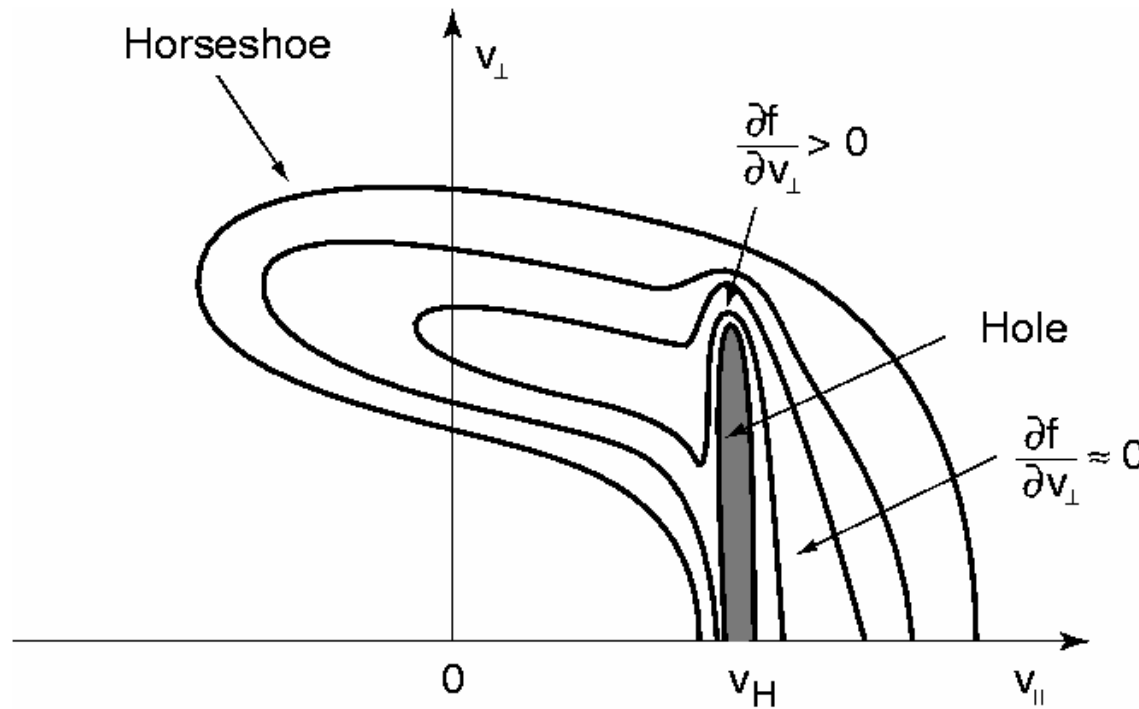
Growth rate :
$$\frac{\omega_i}{\Omega_e} \sim \frac{\omega_p^2}{\Omega_e^2} \frac{N_r}{N_e} \Omega_e \int d^3 v \frac{\partial F}{\partial v_{\perp}} v_{\perp}^2 \partial \left[\omega_r - \Omega_e \left(1 - \frac{v^2}{2c^2} \right) - k_{//} v_{//} \right]$$

Electron Horseshoe Distribution

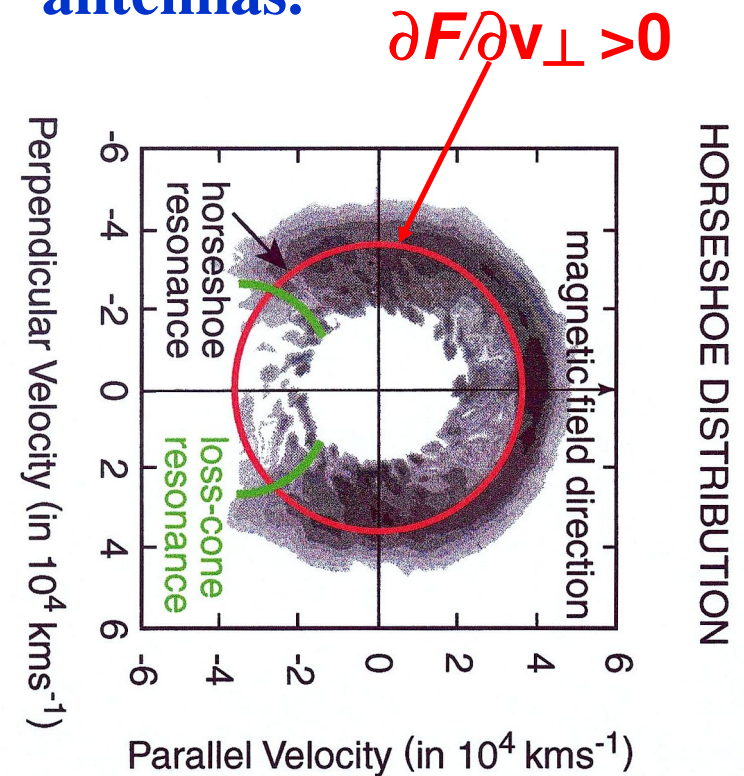


LOCAL DEFORMATION OF THE HORSESHOE DISTRIBUTION

- **Nonlinear structures play the role of localized antennas.**



- **Local density gradients associated with nonlinear structures enhanced the intensity level of the radiation.**



STRUCTURES EMETTRICES: EXTENSION RADIALE ET VITESSE DE DERIVE

La fréquence d'émission est la gyrofréquence f_{ce} , une largeur de bande Δf correspond à une extension radiale Δz de la structure :

$$f_{ce} = f_{c0} \left(\frac{R_E}{R_E + z} \right)^3 \quad \Delta z \sim \frac{R_E}{3} \frac{\Delta f}{f_{ce}}$$

◆ **Dans les régions d'accélération $\Delta z \sim 1 \text{ km}$ pour $\Delta f \sim 200 \text{ Hz}$.**

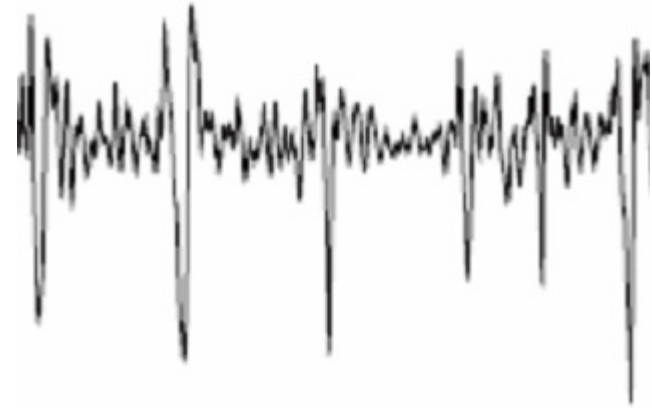
La vitesse radiale de la structure dz/dt peut être obtenue à partir de la valeur mesurée de la dérive en fréquence df/dt :

$$\frac{dz}{dt} = - \frac{R_E}{3} \left(\frac{f_{co}}{f} \right)^{\frac{1}{3}} \frac{1}{f} \frac{df}{dt}$$

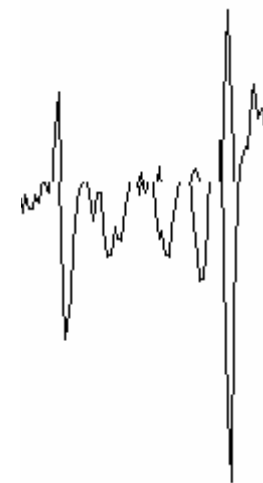
◆ **Pour $df/dt \sim 1 \text{ kHz/s}$, on obtient $dz/dt \sim 10 \text{ km/s}$.**

Asymétrie des émissions RKT au voisinage d'une Double Couche

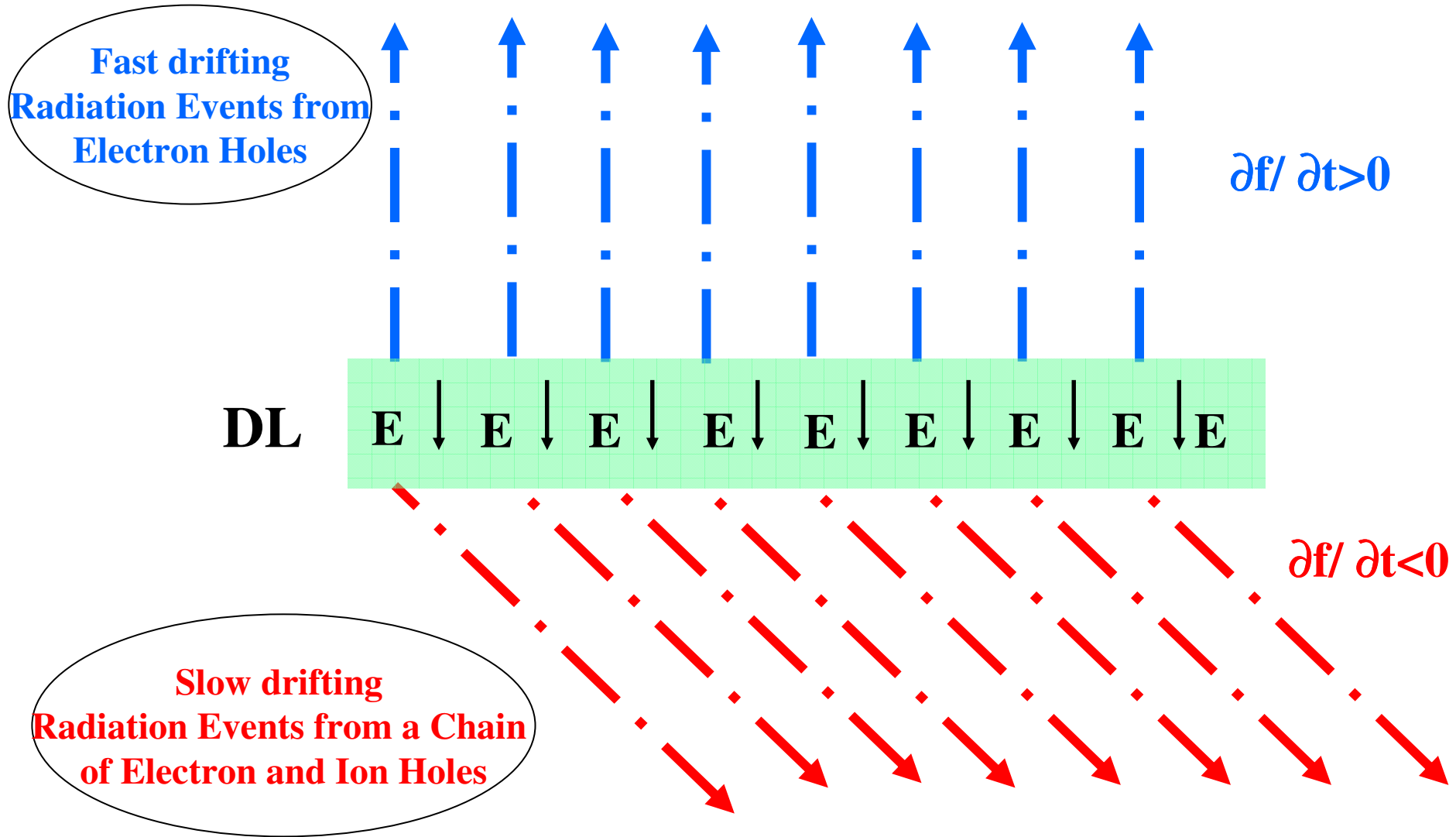
Structures tripolaires se propageant à la vitesse de dérive des faisceaux d'ions (~ 100 km/s):



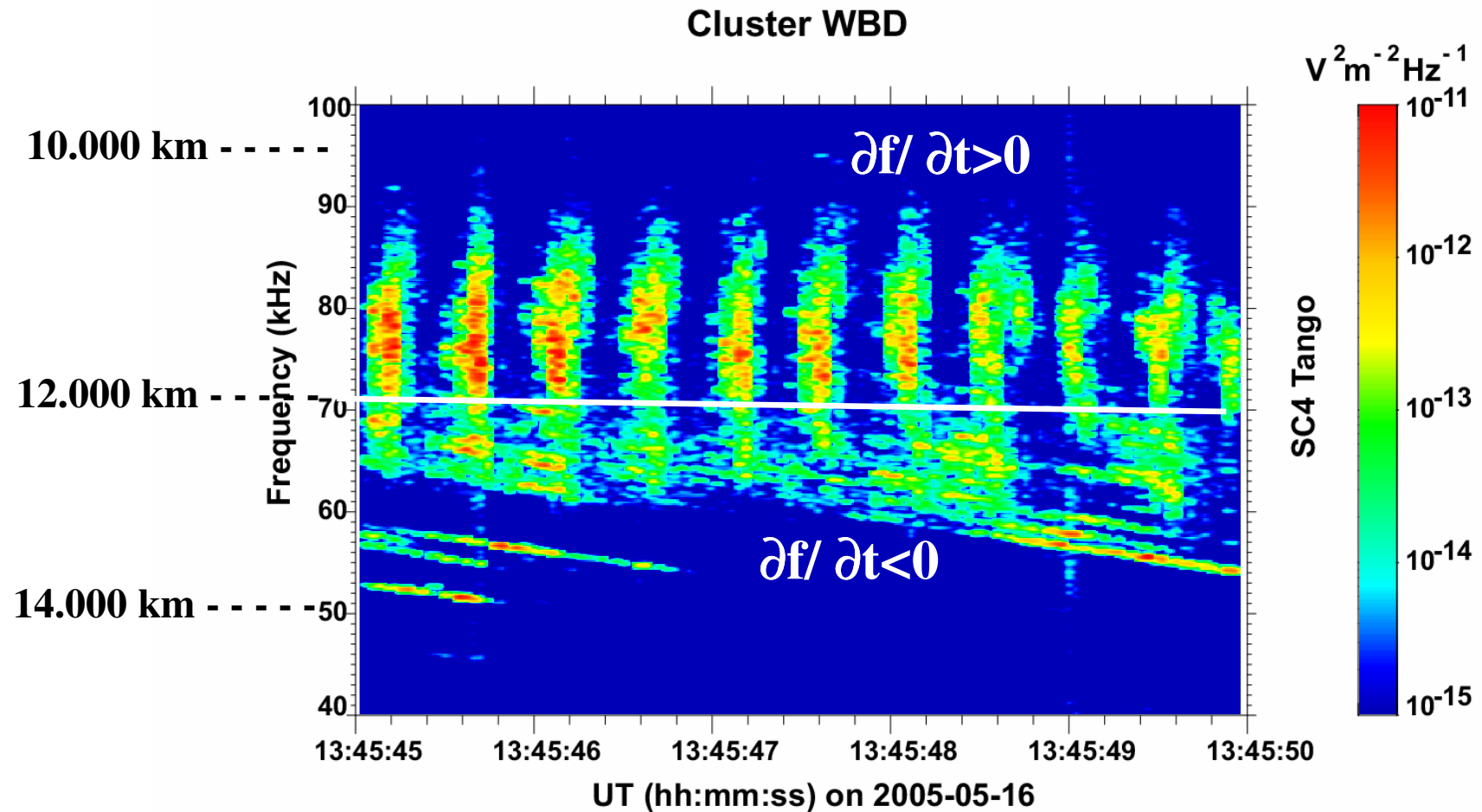
Structures dipolaires se propageant à la vitesse de dérive des faisceaux d'électrons (~ 1000 km/s):



ELEMENTARY RADIATION EVENTS IN THE VICINITY OF A DL



PULSING AKR EMISSIONS DURING RECOVERY PHASE OF A LARGE STORM



Pulsation at 2.8 Hz in the PC1 frequency range

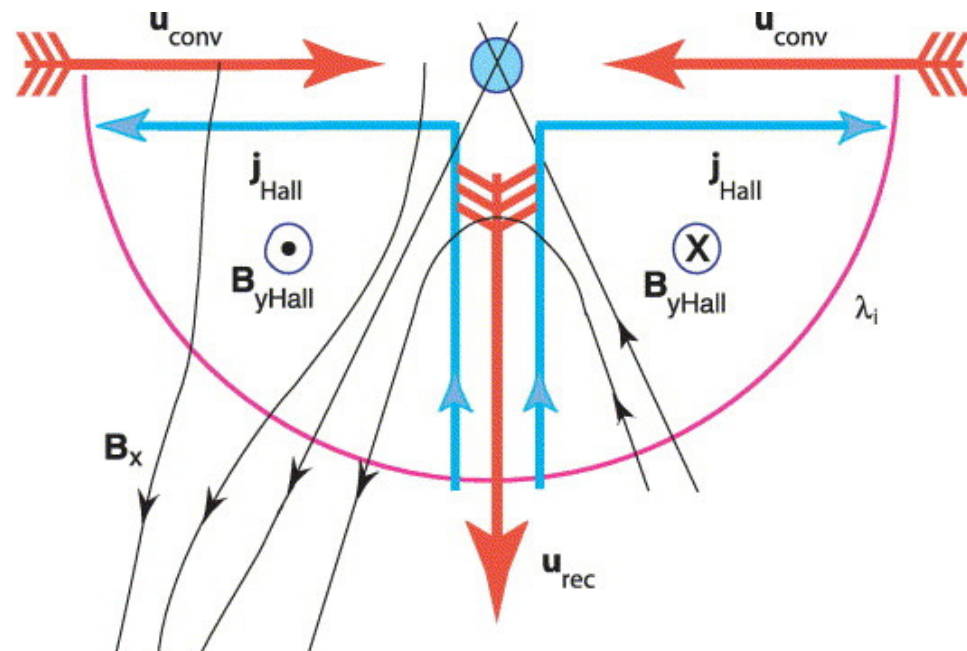
Les mesures à haute résolution temporelle des structures fines du RKT révèlent:

- ◆ *Les dérives fréquentielles mesurées reflètent la présence de « Double Couches » dans les régions d'accélération,*
- ◆ *Les « trous d'électrons » se comportent comme des antennes naturelles plongées dans le plasma,*
- ◆ *La dynamique des « trous d'ions » peut intervenir dans la génération de certaines structures fines du RKT.*

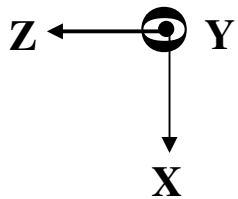
Cette technique de sondage à distance permet d'accéder à la dynamique des processus d'accélération turbulents

TRANSPORT TURBULENT / STRUCTURES FILAMENTEUSES

1000 km

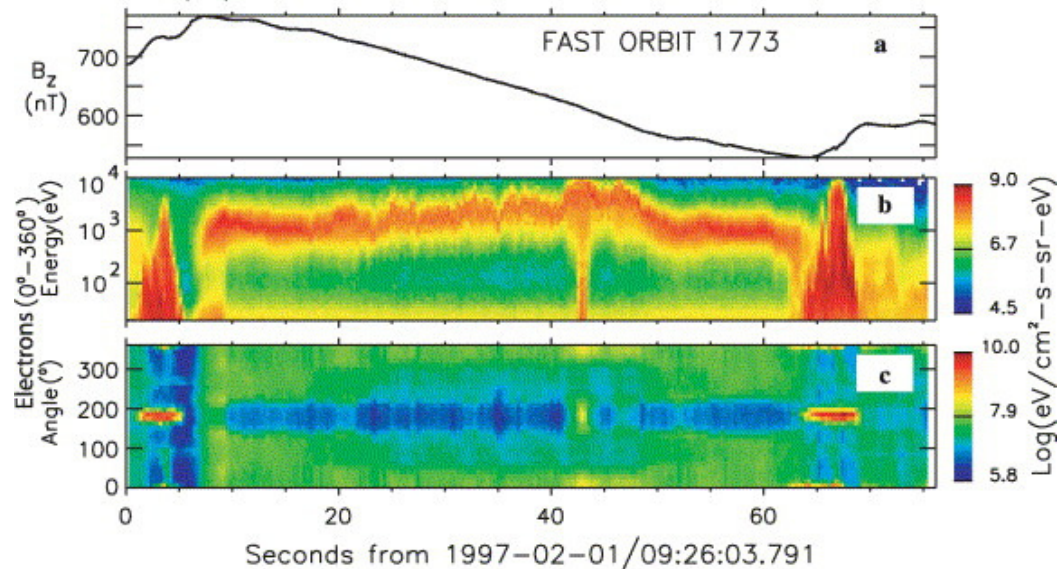


*Earthward half
of the ion
diffusion region*



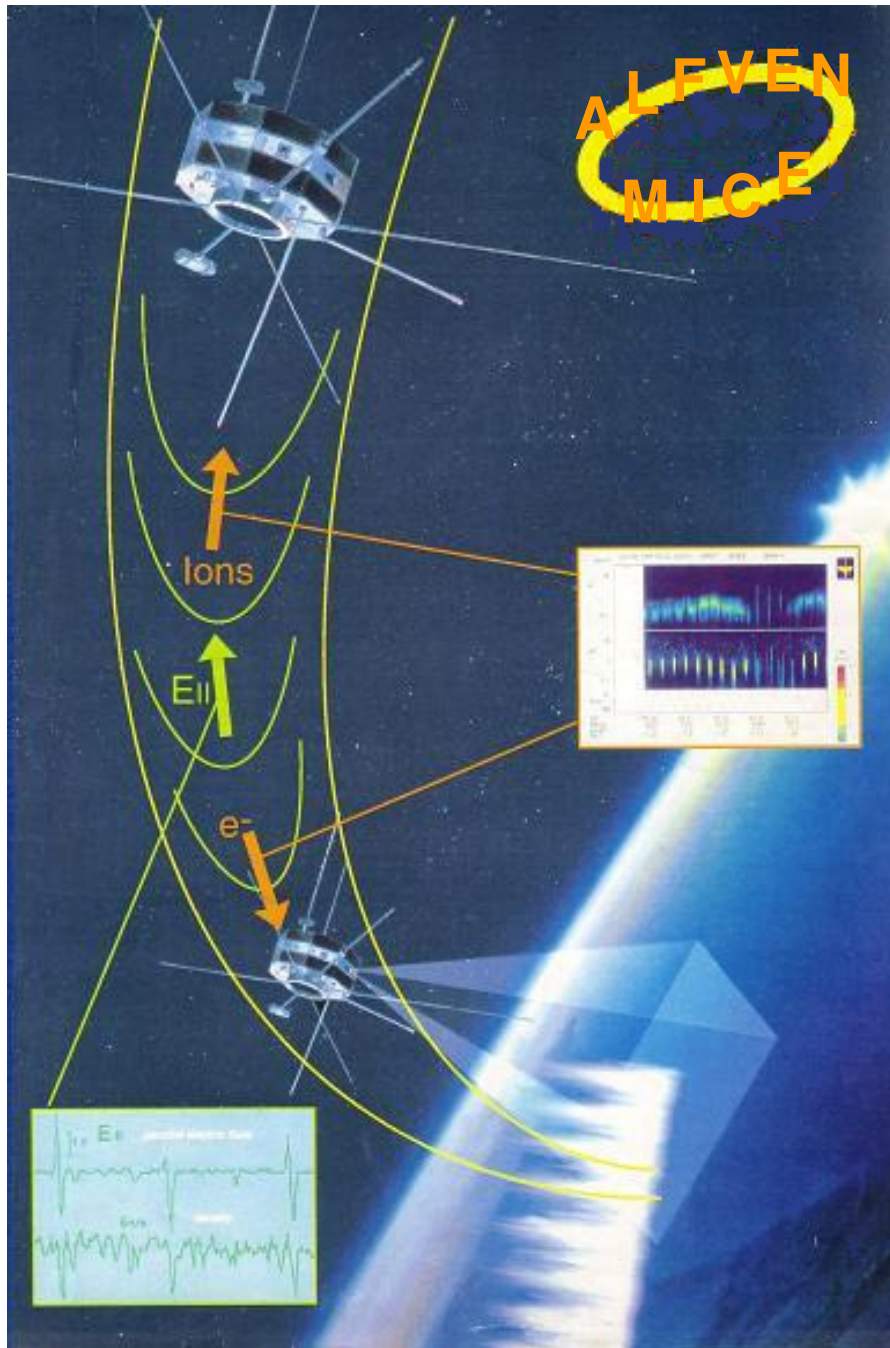
10 km

Double Layer



100 m





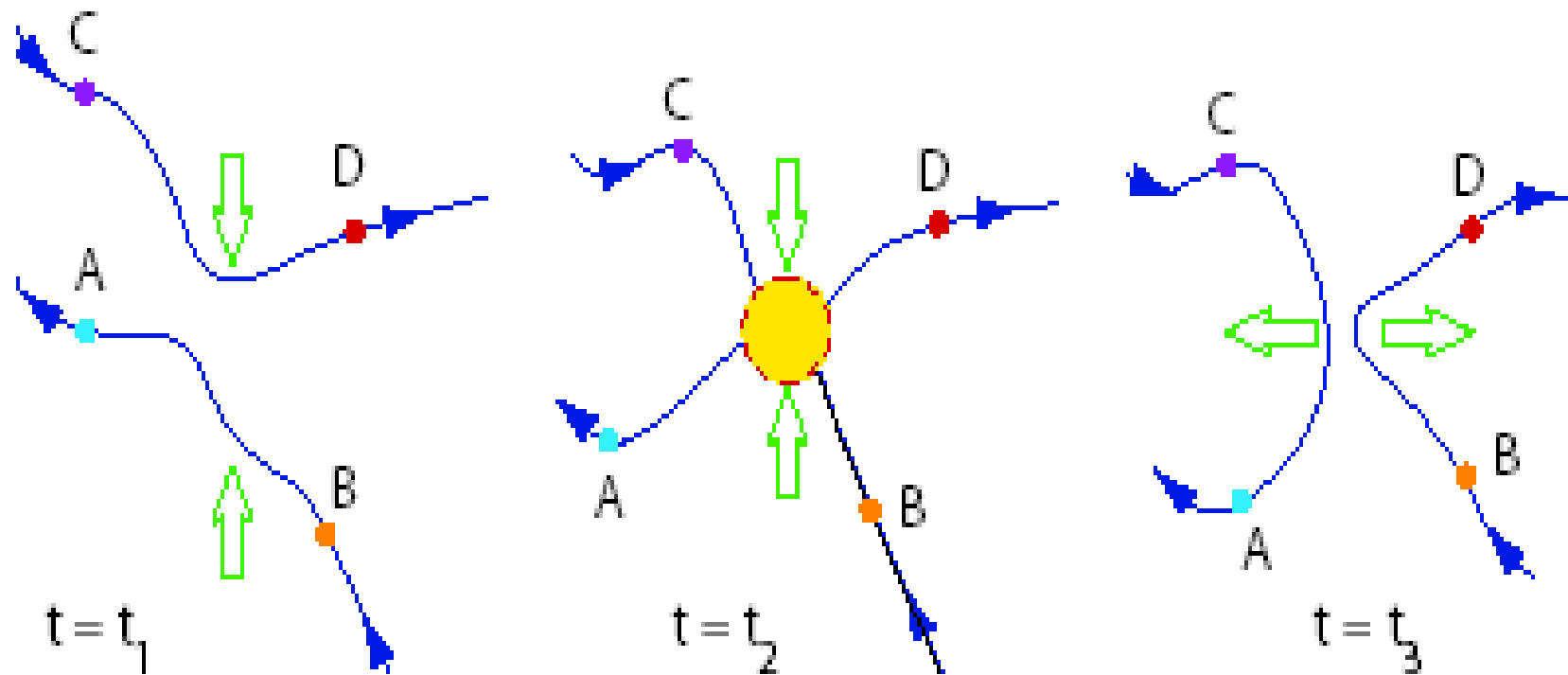
Small-scale processes regulate the interactions between large scales:

Necessity to understand nonlinearly interacting global and microscopic processes on a hierarchy of scales,

Fine structures and rapid temporal changes are the very essence of the transport and exchanges processes in the auroral region,

One needs several spacecraft **equipped with high time resolution experiment** to investigate the microprocesses, assess the **size of the microscopic structures**, and to **distinguish spatial from temporal variations**.

The Meaning of Reconnection



Axford 1984

Auroral zones

Earth

Solar wind

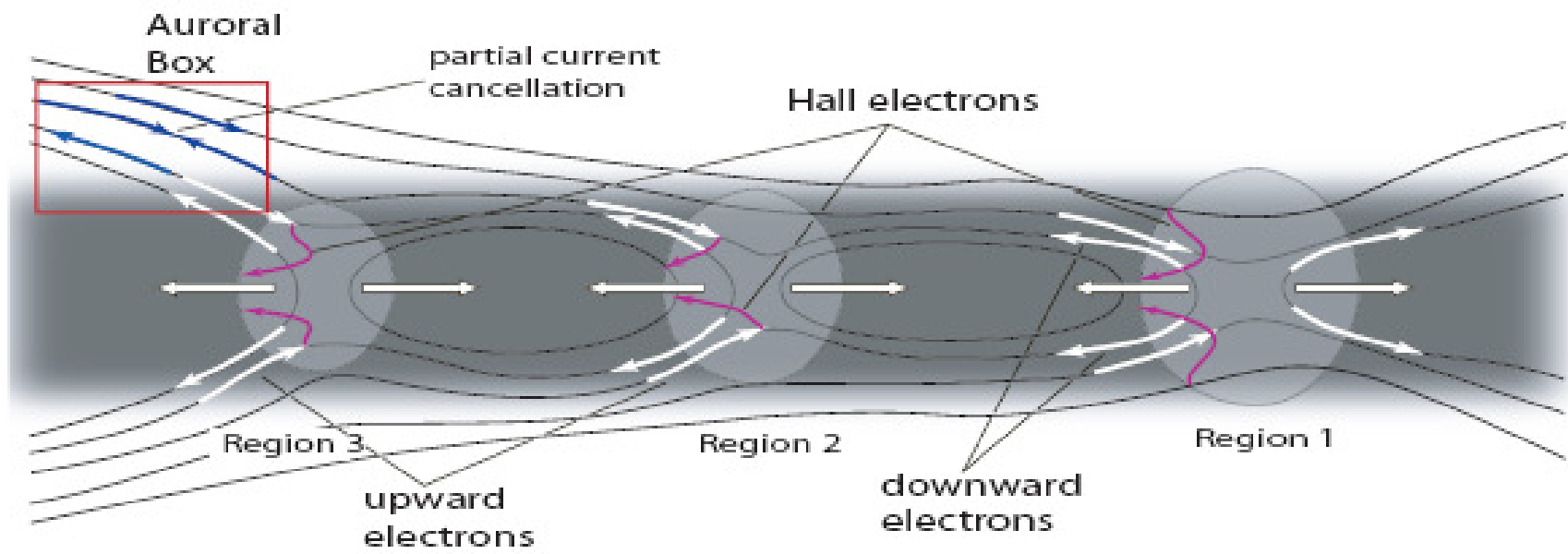
Electron acceleration (10 keV)
Aurorae

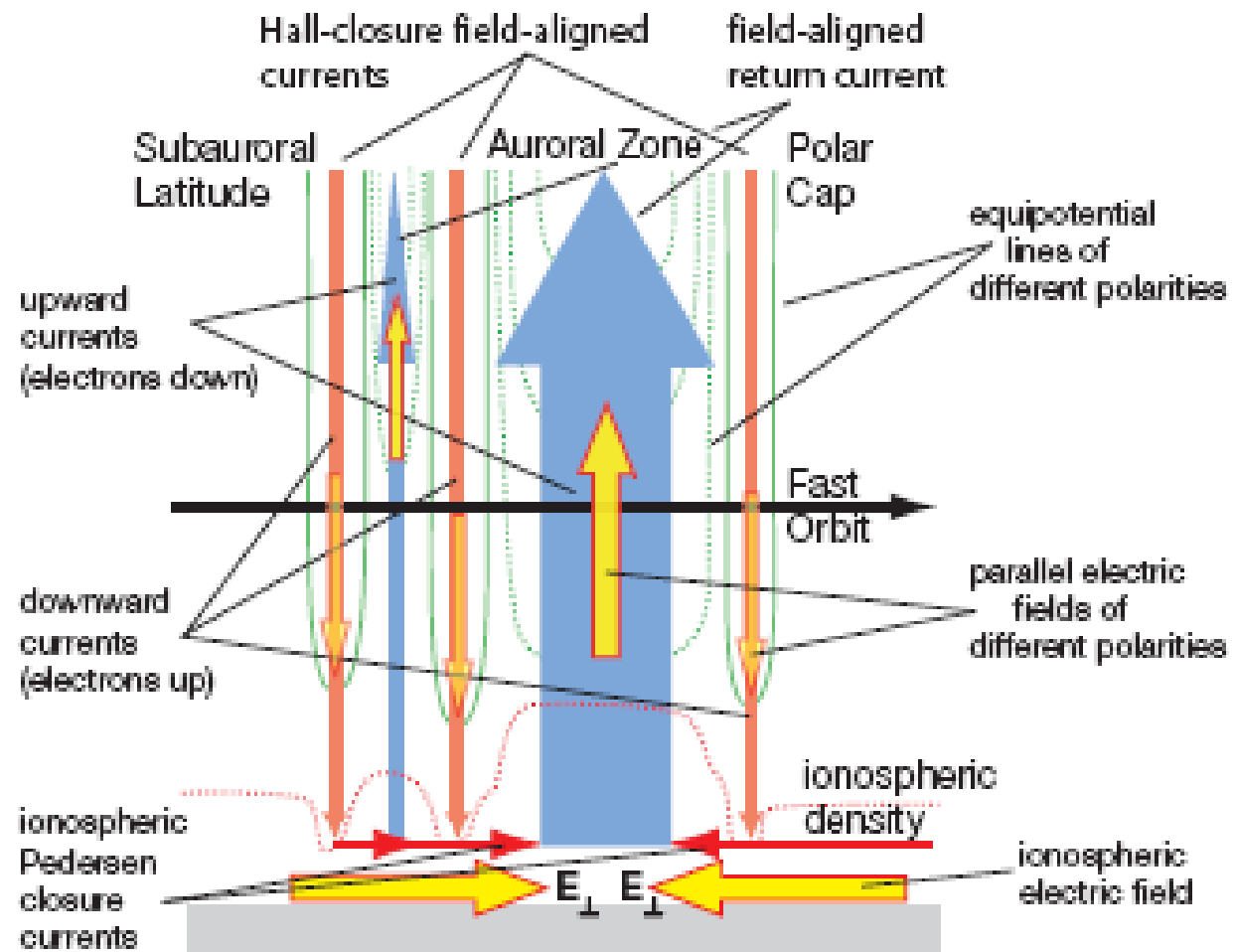
Ion heating/acceleration
 O^+ ions loss (3 kg s^{-1})

Terrestrial kilometric radiation
(10^9 W)

Phase-Space Holes

- Debye scale, large amplitude solitary potential structures with trapped-particle populations
- Formation of phase-space holes occurs in the nonlinear phase of a plasma instability (Buneman,..)
- As the growing plasma waves obtain sufficient amplitude they can trap substantial amount of plasma particles





Evolution of the Auroral Acceleration Region

- How does the system evolve from Alfvénic aurora at the onset of a substorm to a quasi-static situation with particle acceleration through potential drops?

Structure of the Auroral Acceleration Region

- Formation of $\Delta\Phi_{\parallel}$ and E_{\parallel}
- Altitude distribution of $\Delta\Phi_{\parallel}$ and E_{\parallel}
- Are there ion and electron transition regions?
- I-V relation for downward FACs
- Coupling to the ionosphere
- Role of other sinks of electromagnetic energy (wave-particle interactions, radio emission, small-scale vortex formation?)

Other aspects of aurora awaiting definitive explanation

- Creation of narrow arcs (sub-km)
- Diffuse aurora (including fine structure)
- Pulsating aurora
- Coupling between scales