Auroral Kilometric Radiation Generation in the Neighborhood of a Double Layer

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Geospace Revisited

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Earth is an intense radio source, closely associated with auroral acceleration process:

- **First observed by Elektron satellites [Benedikov et al, 1965]**
- **Frequency range : 30-700 kHz, spectrum peaks at 300 kHz**
- **Total power ~ 10^7 W with peak power level reaching 10^9 W,**
- **High electron - to – radiation energy conversion efficiency : 1%**
- **Source regions correlate with discrete auroral arcs [Gurnett, 1974]**
- **Direct consequence of the parallel acceleration processes.**

CYCLOTRON MASER INSTABILITY LEADS TO AKR GENERATION:

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

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

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

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

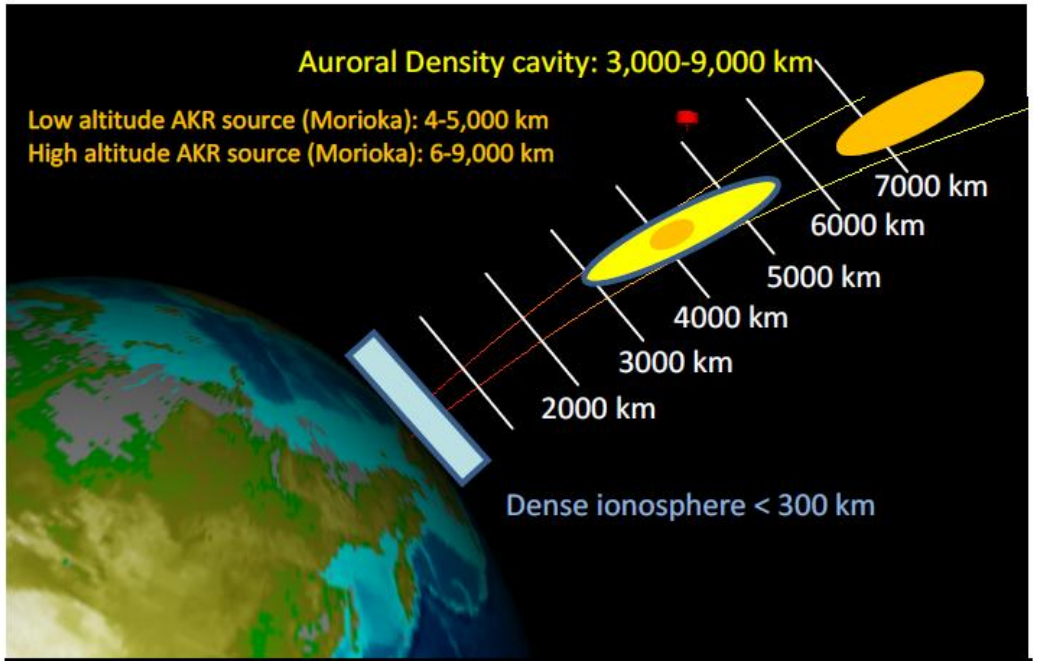
For $k_{//} = 0$ Emission at $\omega < \Omega_e$

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

X-mode growth rate :

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

Remote sensing of Substorm ignition thanks to AKR dynamic behavior



Two-step evolution at substorm onset:

- Low altitude acceleration (4-5000 km) ➡ **Initial auroral brigthening**
- Abrupt high altitude acceleration (above 6000 km) ➡ **Auroral breakup**

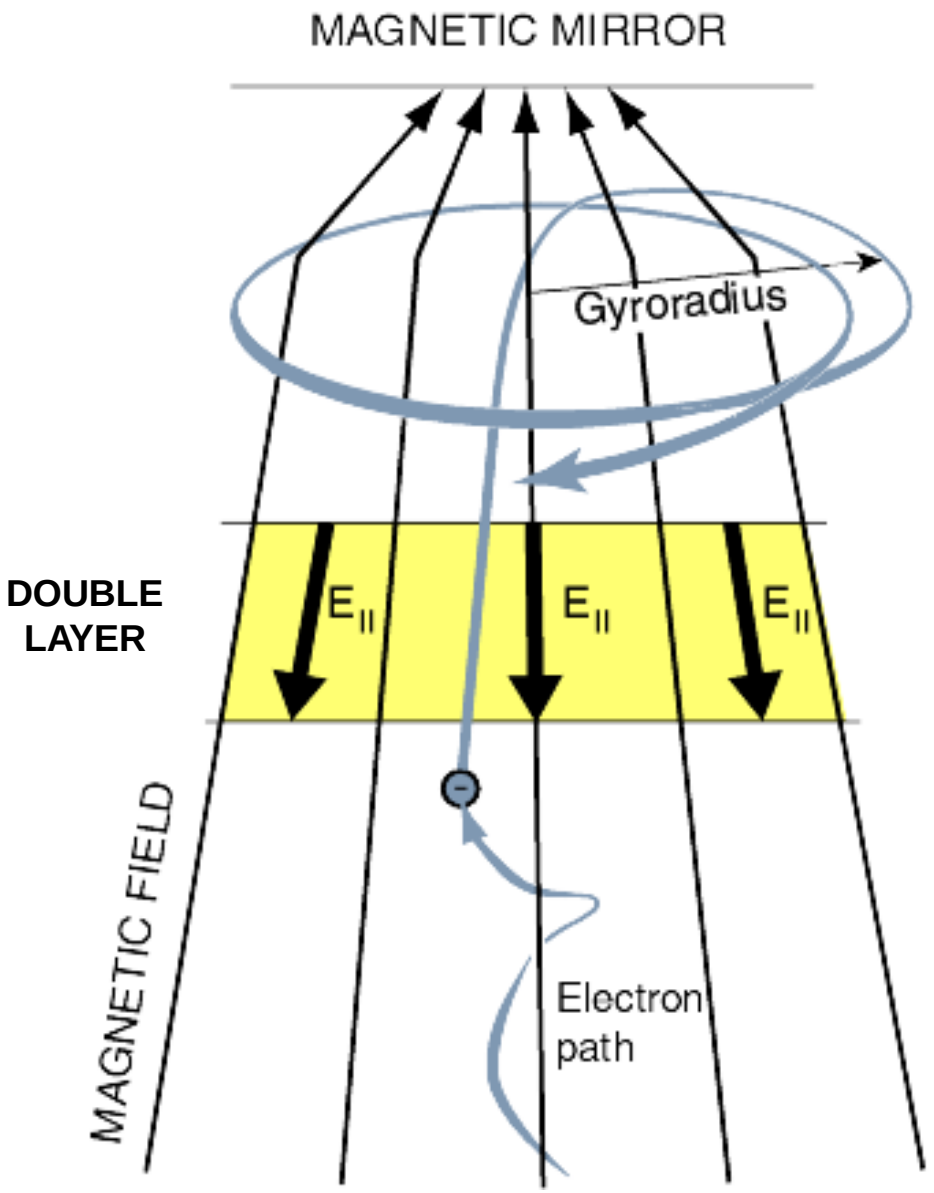
Morioka, 2010

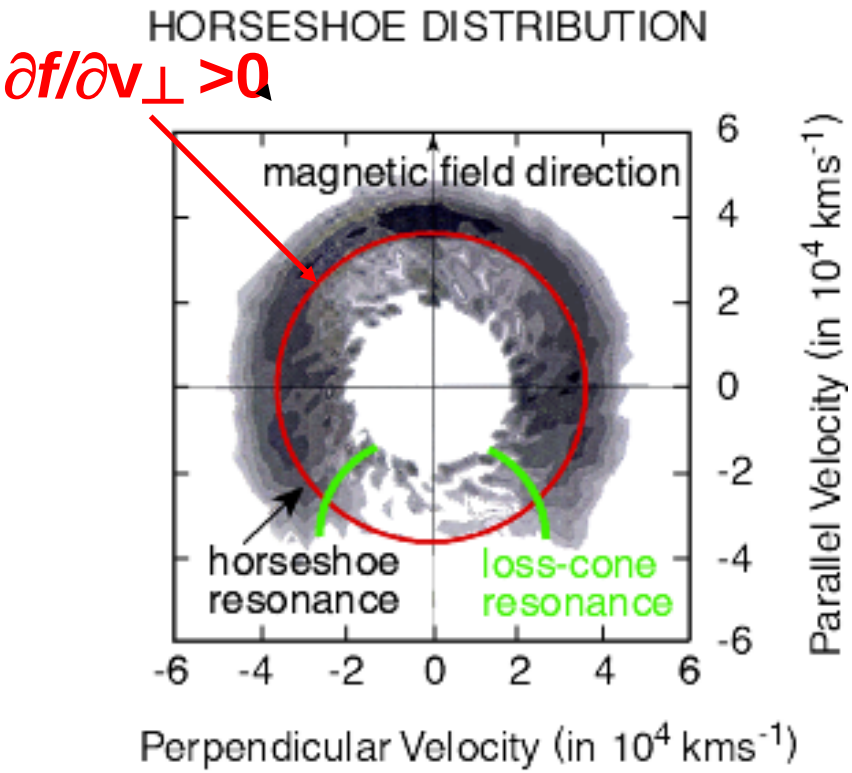
Where Does the Free Energy Come From?

- The radiation contains fundamental information on the characteristic spatial and temporal scales of the turbulent accelerating layers;

- The anti-earthward directed parallel electric field generates an unstable electron distribution which provides the free energy for the radiation.

Electron Horseshoe Distribution





Ergun et al., 2001

The simple picture of AKR generation solely by the global "horseshoe" distribution might be incomplete because:

- ***The growth rate becomes significant far away from the location where the electrons have been accelerated by the DLs !***

There is a need to determine in the neighbourhood of a DL:

- ***What kind of electron distribution is present?***
- ***How does the plasma radiate?***

OUTLINE

Study of strong turbulent processes in the AKR source region:

- **Double Layers can support a parallel potential jump confined to a narrow spatial region,**
- **DLs accelerate particles along the magnetic field lines and generate locally strong turbulent processes leading to the formation of phase space holes,**
- **Phase space holes may act as localized antennas and may produce the elementary radiation events recorded in the AKR spectrum?**

DOUBLE LAYERS
ELECTROSTATIC SHOCKS

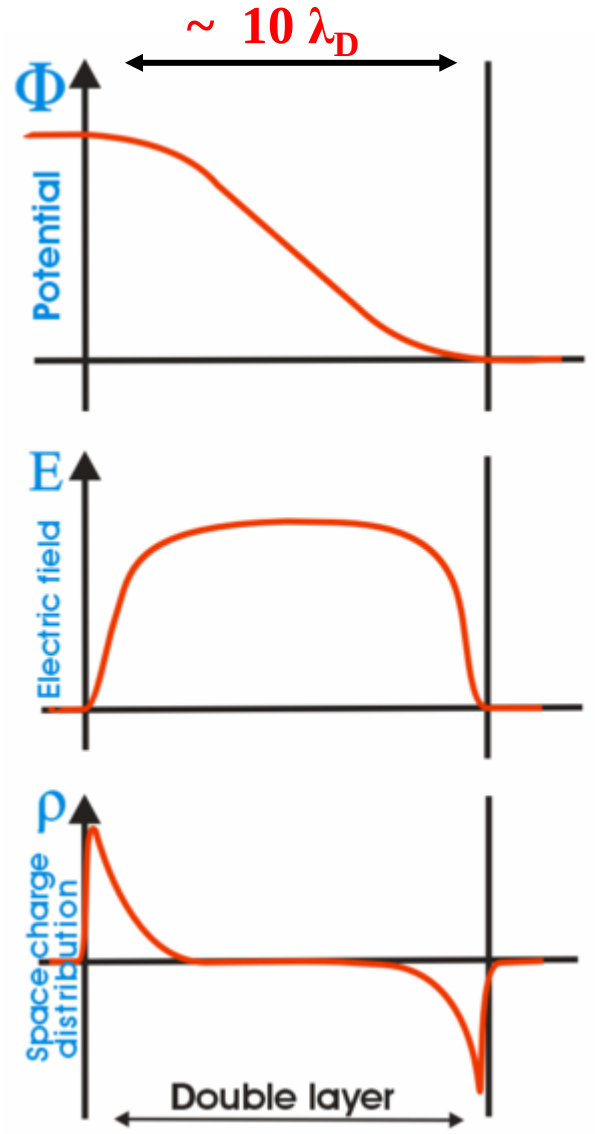
♦Nonlinear structures that can sustain a local region of parallel electric field,

♦First advocated by ***Alfven (1958)*** in an astrophysical context:

- Effective dissipation mechanism for solitary Alfven waves carrying substantial currents?

- Evolution from large amplitude ion-acoustic waves in a multi component plasma?

♦**Radiation from DLs may explain observed intense and narrow band bursts from stellar and planetary magnetospheres**



ELECTRIC POTENTIAL DROP ACROSS A DL

Energy Conservation Law: $\left| j_{//} E_{//} \right| \approx d(n_e k_B T_e)/dt$

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

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

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

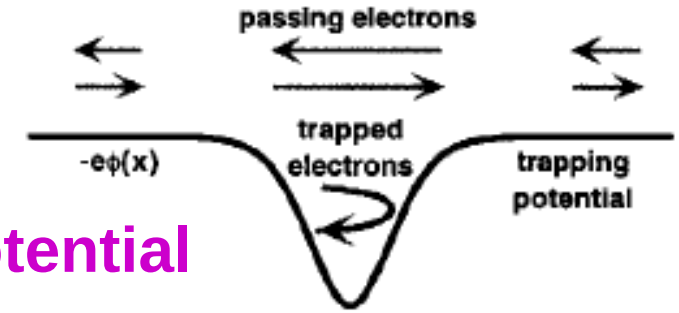
Pottelette and Pickett, 2007

DLs and Phase-Space Holes Generation

By accelerating particles along the magnetic field lines DLs serve as the generator of a large number of 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 waves obtain sufficient amplitude they can trap a substantial amount of plasma particles.**

Phase-space Hole Formation Mechanism



Potential

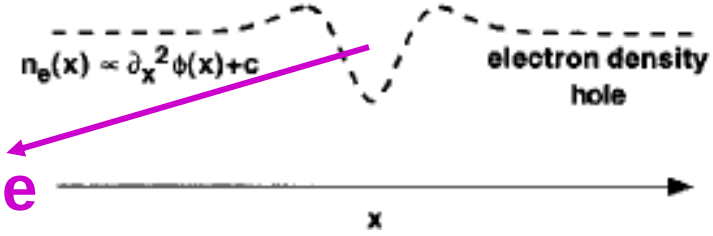
passing

trapped

} Phase space distribution

Field

Density



Hole

Real space distance

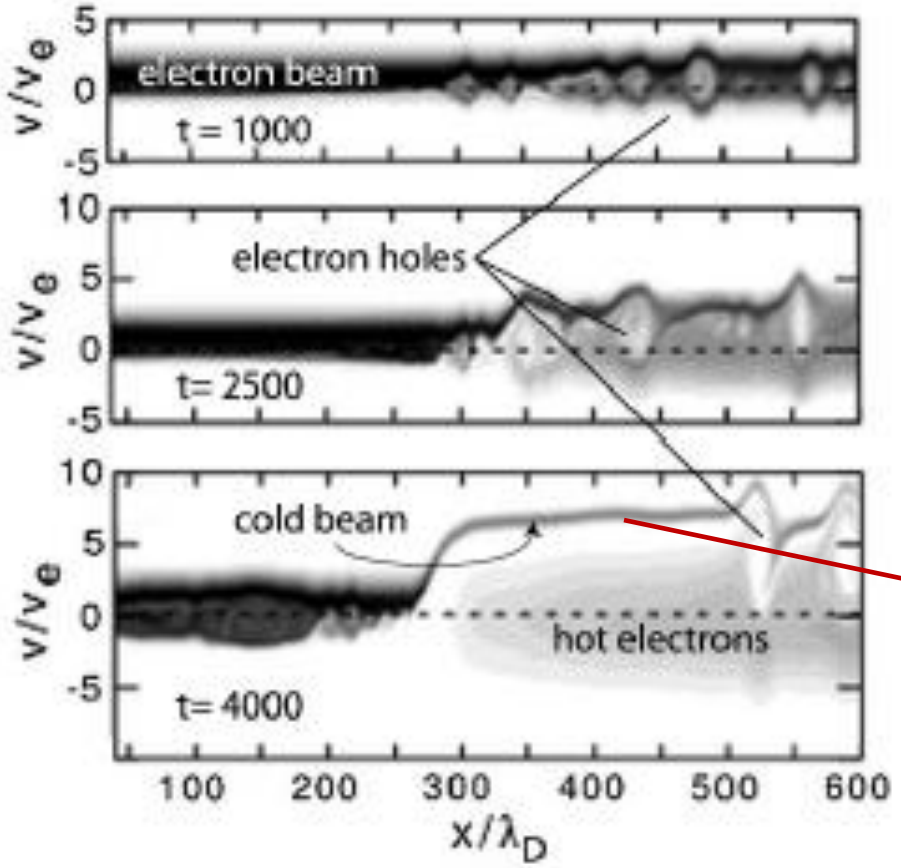
Nonlinear interaction between plasma waves and particles on the Debye scale:

- **Electron holes (positively charged)**
- **Ion holes (negatively charged)**

(Goldman et al. 1999)

Numerical Simulation of the Formation of Electron Holes

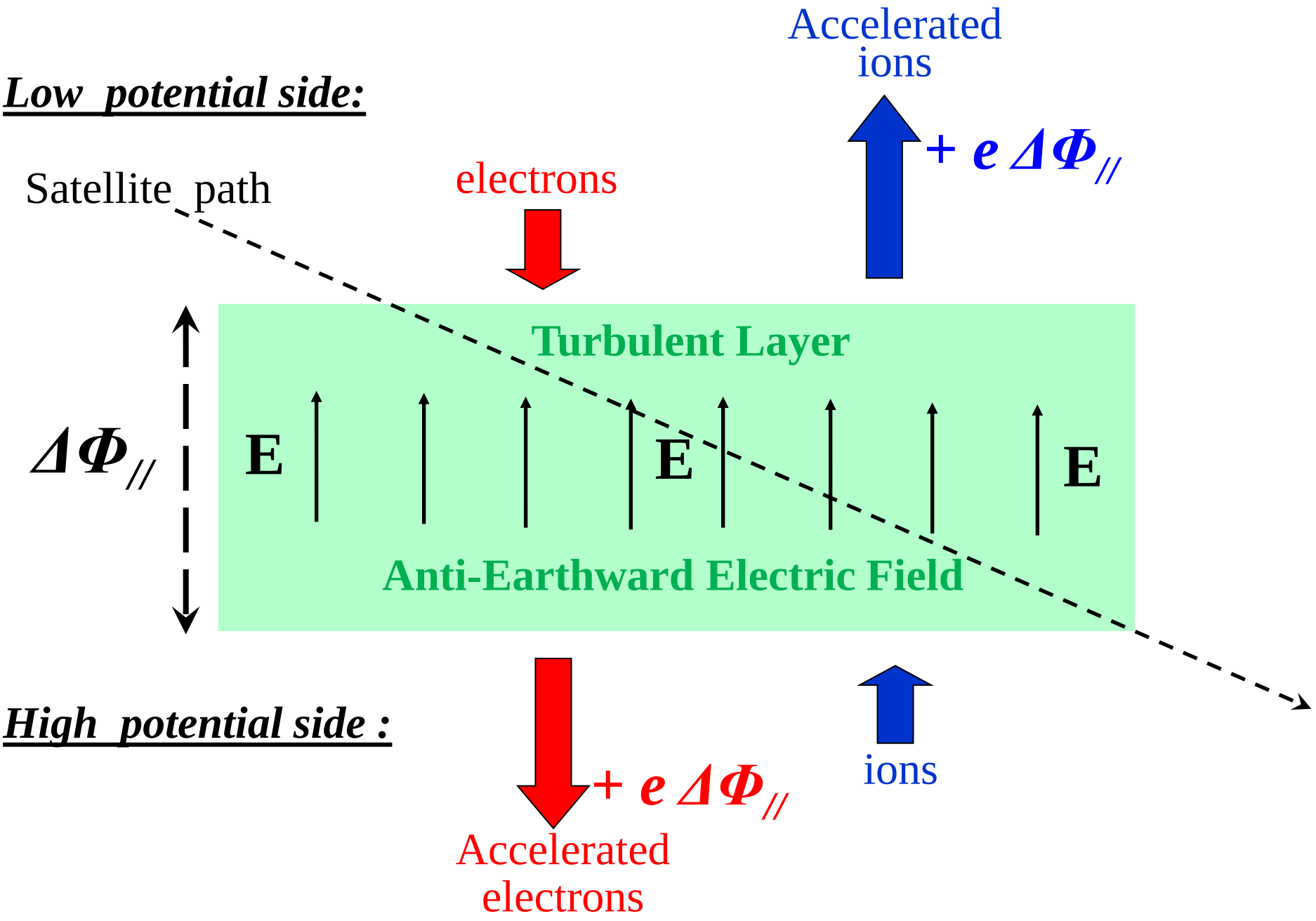
Beam-Plasma Interaction



Steep positive velocity gradient

The initial hot beam is split into a very cold beam and a very dilute hot trapped electron distribution.

(Newman et al., 2002)

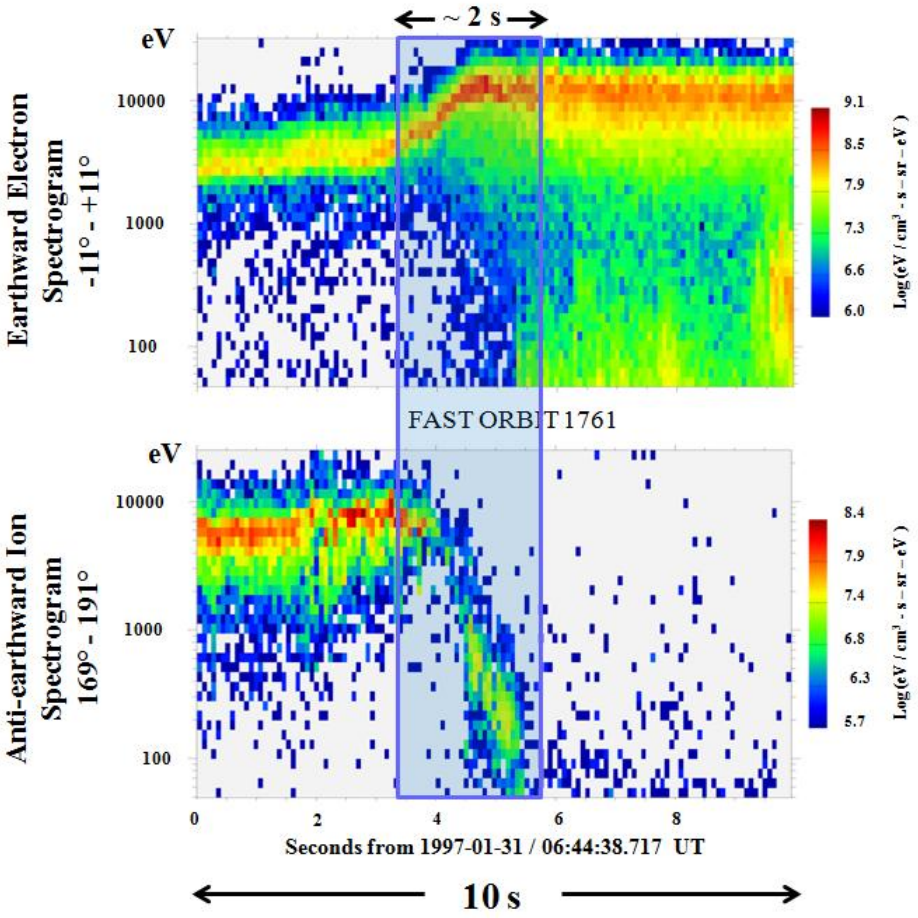

Low potential side:
Satellite path
electrons
Accelerated ions
+ e ΔΦ//
Turbulent Layer
ΔΦ//
E
E
E
Anti-Earthward Electric Field
High potential side :
+ e ΔΦ//
Accelerated electrons
ions

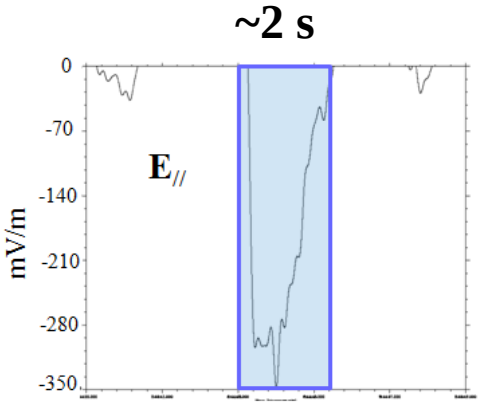
CROSSING OF A DOUBLE LAYER

ELECTRON-ION ANTI-CORRELATION PARALLEL ENERGIES

$\Delta\Phi_{//} \sim 8\ kV$

$\Delta L_{//} \sim 25\ km$

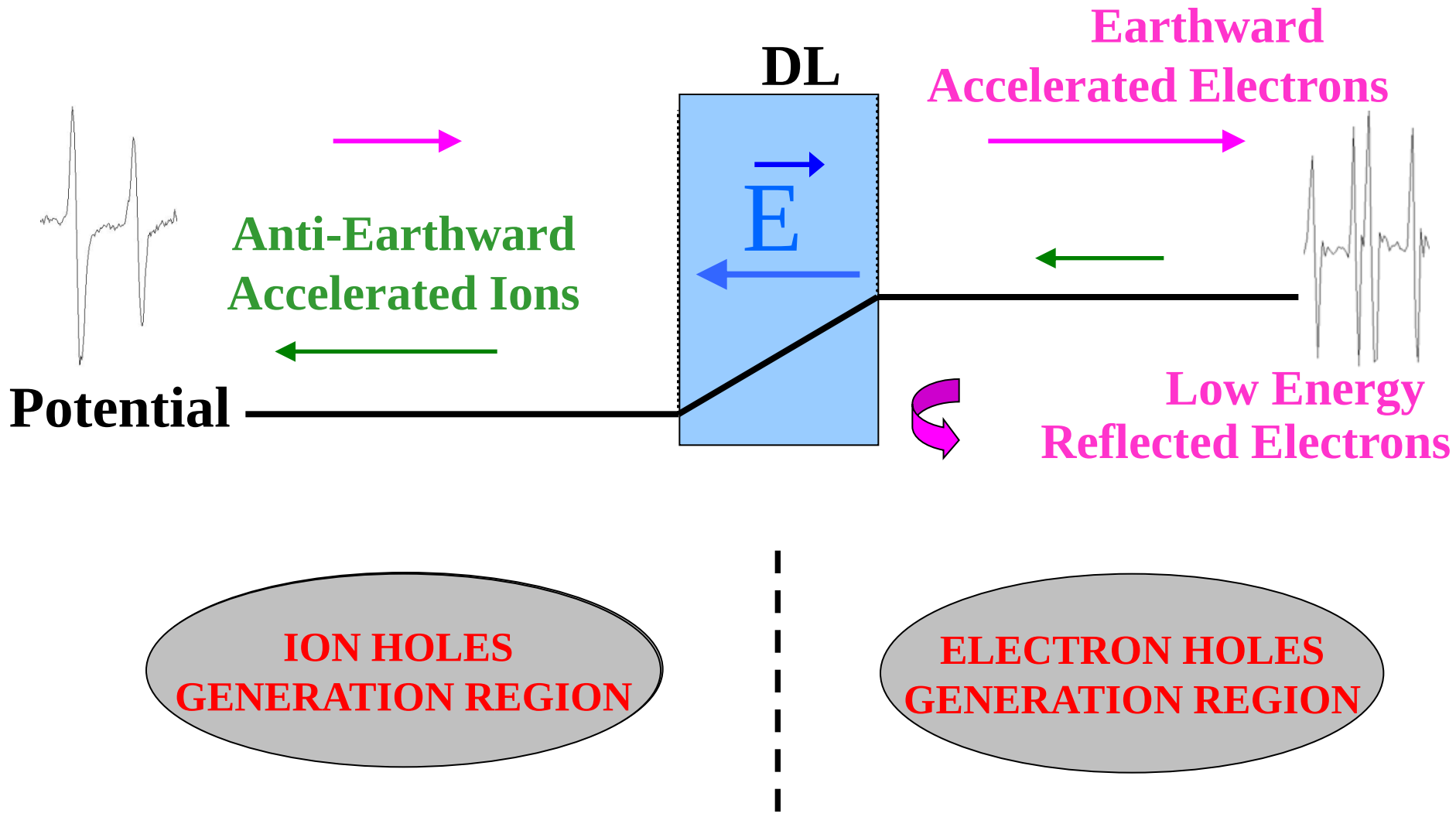




$E_{//}$ field ~ 300 mV/m (anti -earthward)

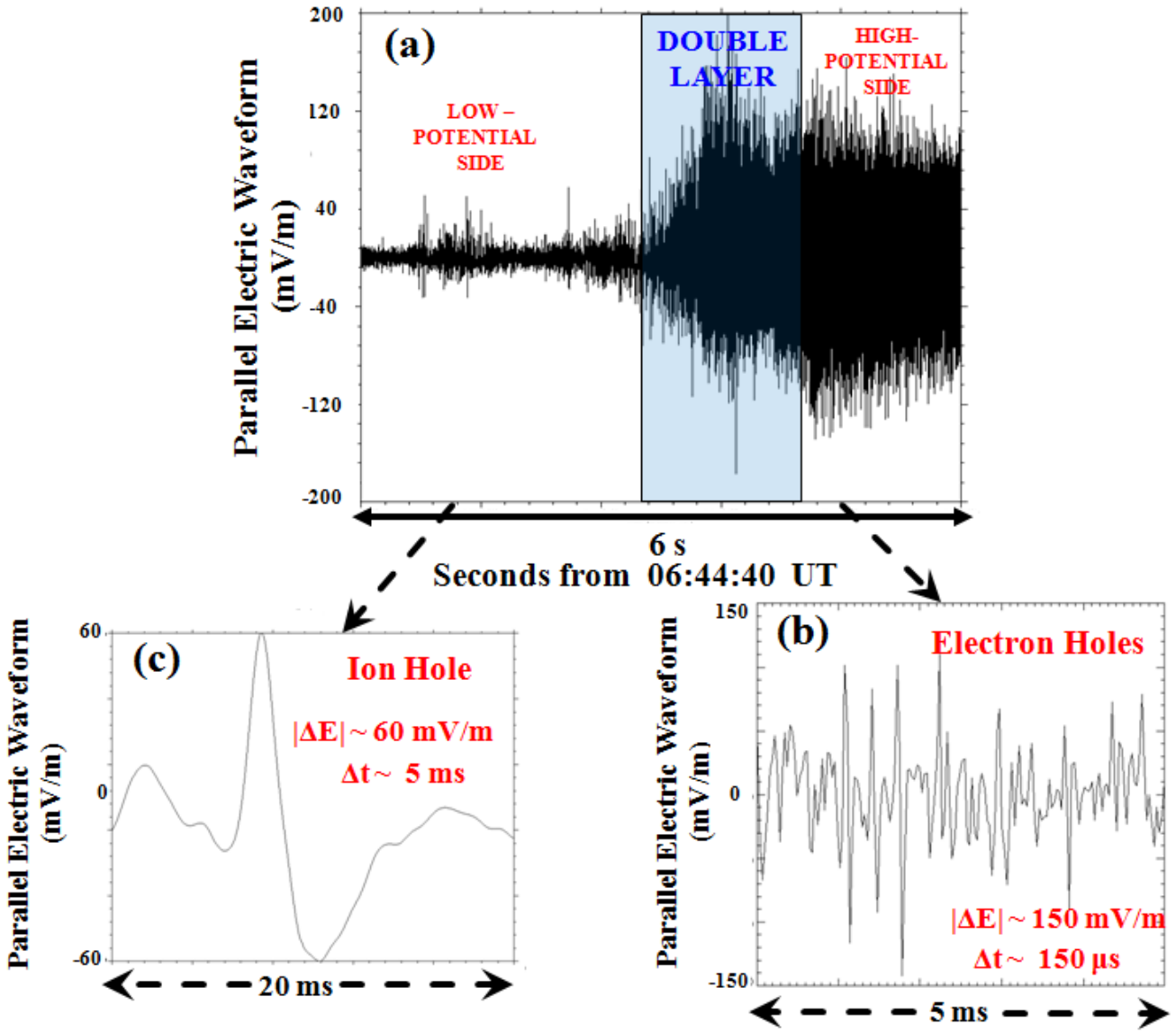
FAST spacecraft

Turbulence generated by a localized DL

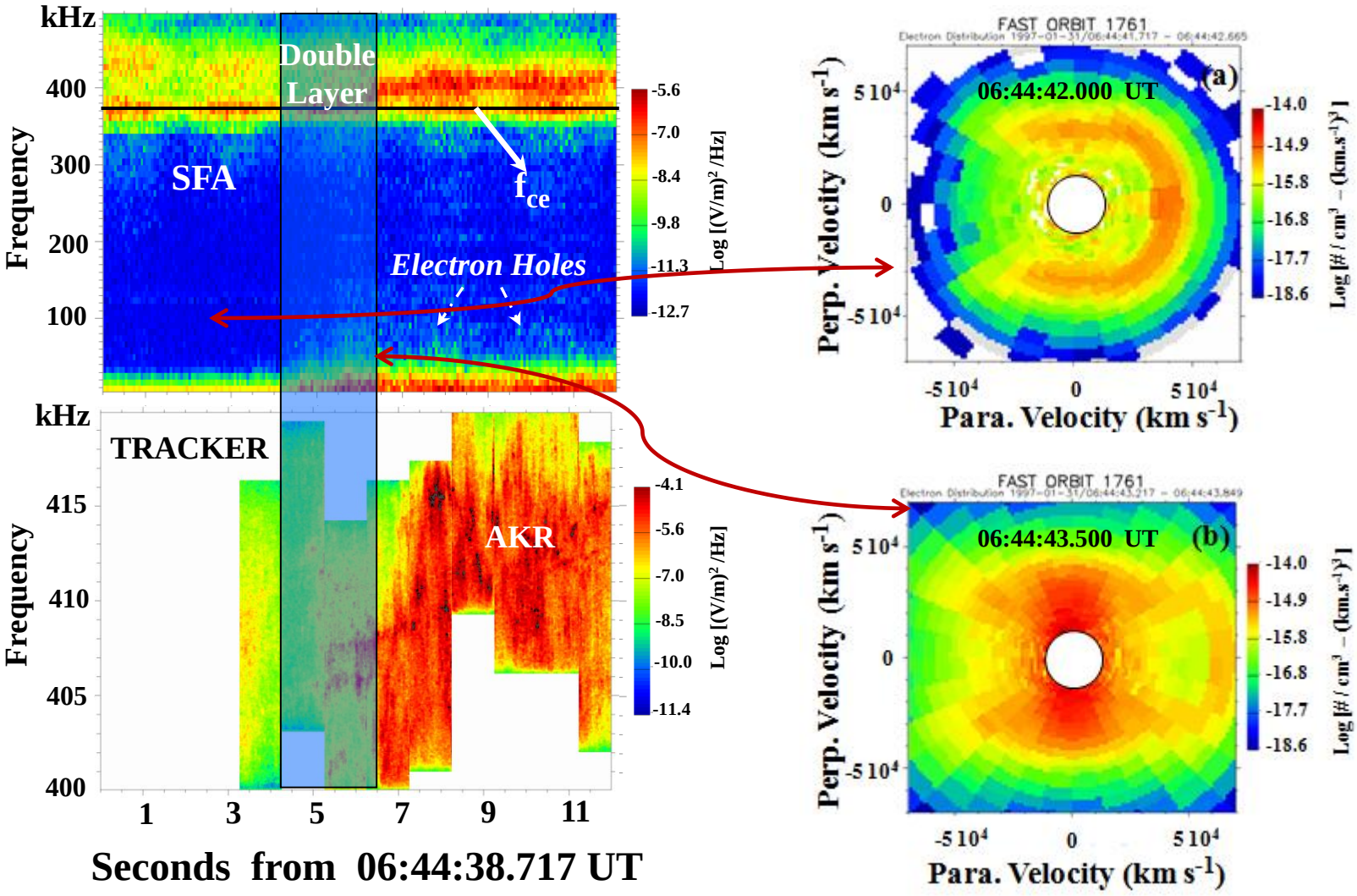


PHASE SPACE HOLES IN THE VICINITY OF A DOUBLE LAYER

Parallel Electric Field Waveform



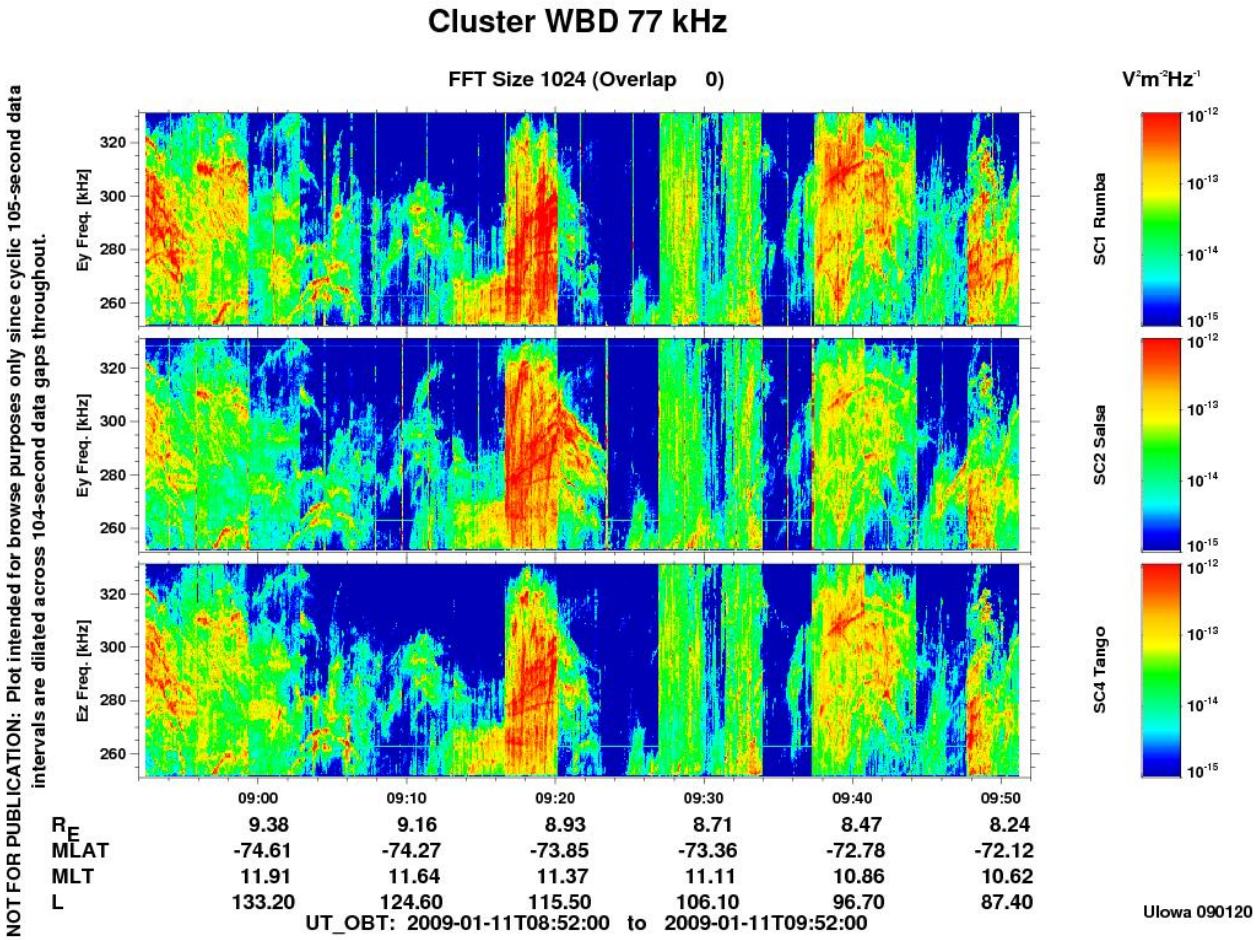
RADIATION IN THE NEIGHBOURHOOD OF A DL



Pottelette et al, 2014

FAST spacecraft records drifting AKR fine structures **above the electron gyrofrequency** in association with :

- Double layers
- Enhanced density structures
- Presence of electron holes

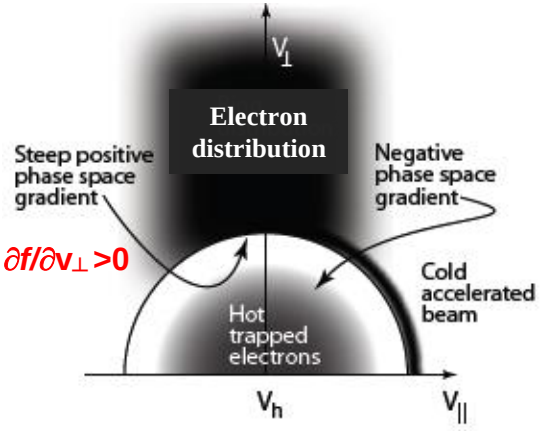


AKR consists of many discrete narrow band emission (~ 1kHz)

A bandwidth Δf~1kHz corresponds to a radial size Δz~0.5 km of the elementary radiation structures:

Presence of electron holes with scale size a few Debye lengths?

Electron beam-plasma interaction leads to fast electron holes generation:



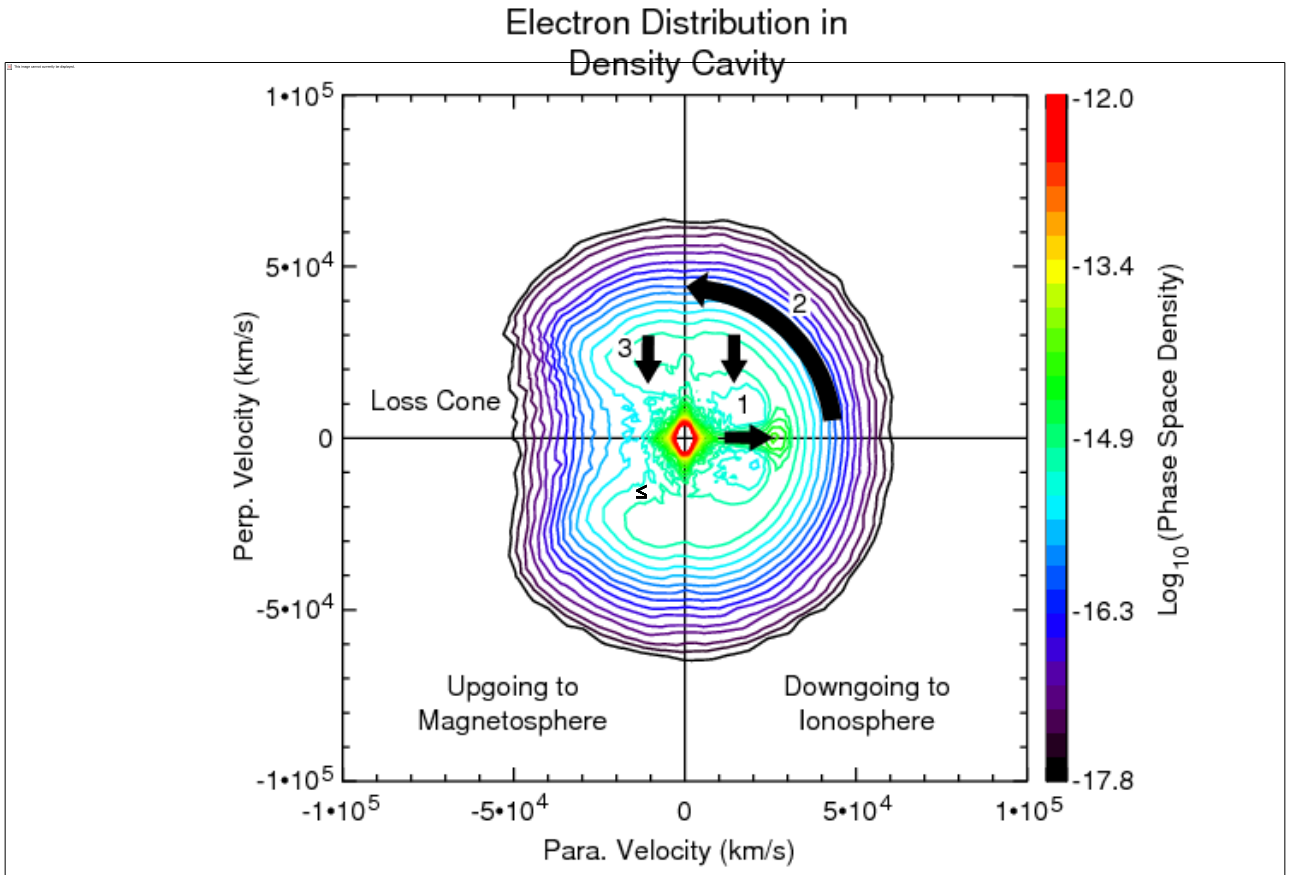
Treumann et al, 2011

- For $\omega_p << \Omega_e$, EHs have a spherical shape ***(Berthomier, 2003)***,
- Steep positive velocity space gradients on the electron distribution function,
- Consequent growth rate at the edges of the density cavity: $\frac{\gamma}{\Omega_e} \approx \frac{\pi^3}{8} \frac{n_b}{n_e} \frac{\omega_p^2}{\Omega_e^2}$

Electron holes are well suited to:

- **Generate oblique radiation**
- **Frequency range not restricted to the electron gyrofrequency**

DIFFERENT RADIATIVE PHASES



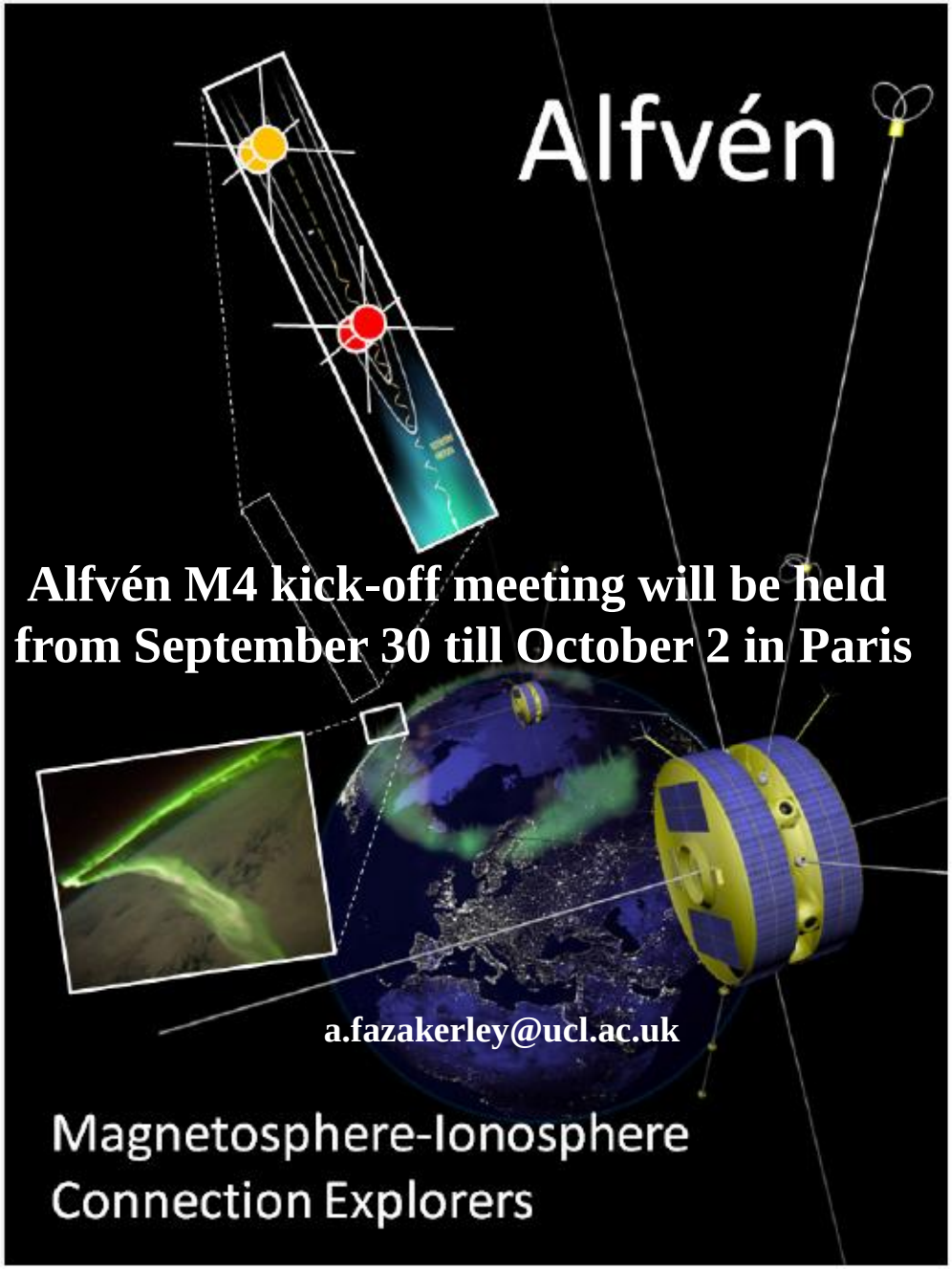
1) Parallel acceleration by electric field: **radiation from electron holes above F_{ce} ?**
2) Horseshoe distribution function due to mirroring effects: **radiation at $\leq F_{ce}$**

Several fundamental questions regarding the generation processes of AKR remain unanswered:

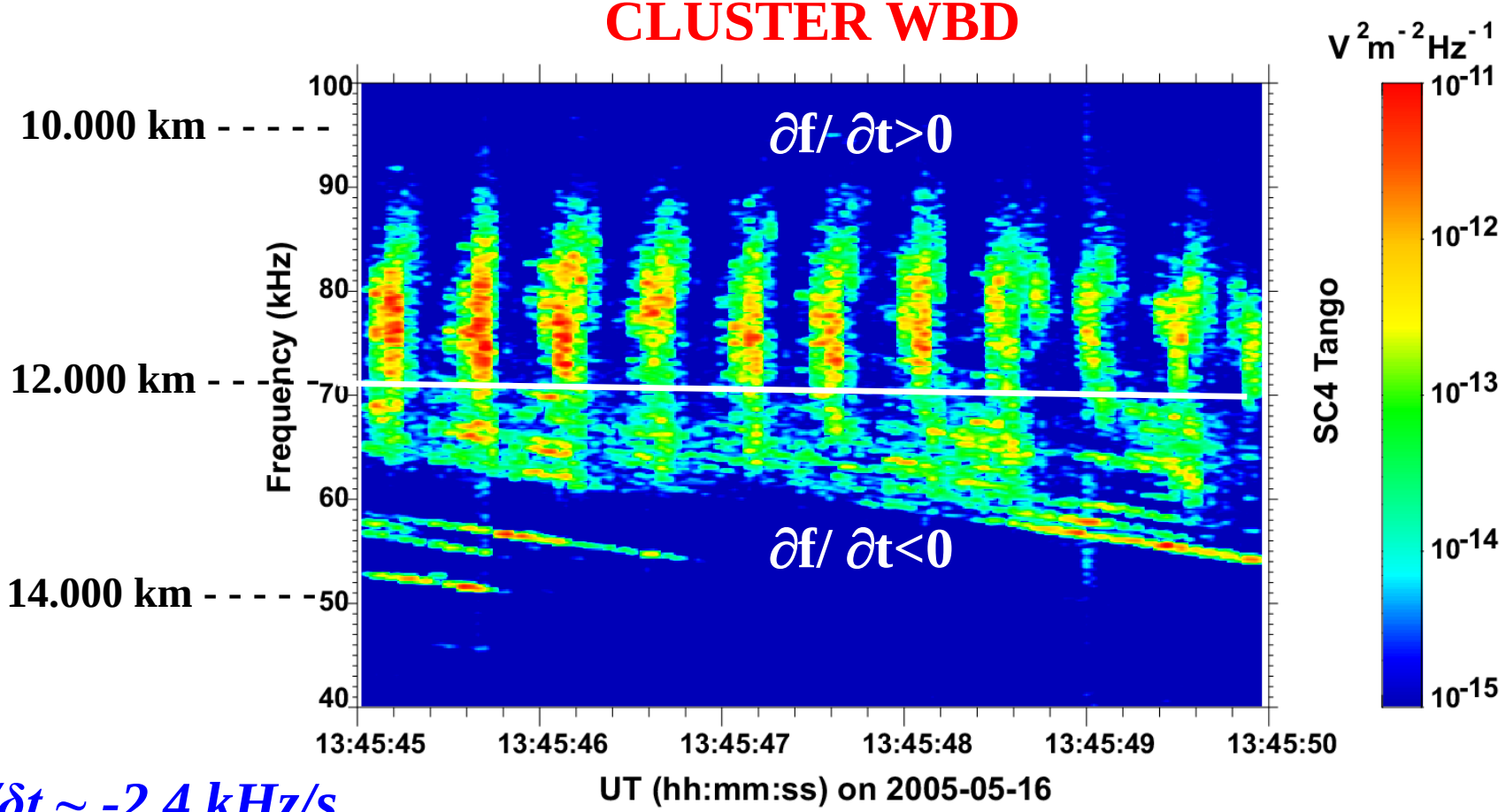
- **How does the radiation evolve from the place where the electrons have been accelerated?**

- **The enormous fine structuring of the radiation which seems to reflect the intrinsic properties of the source itself ?**

- **The way the radiation escapes from the local density cavities where it is generated?**


Alfvén
Alfvén M4 kick-off meeting will be held from September 30 till October 2 in Paris
a.fazakerley@ucl.ac.uk
Magnetosphere-Ionosphere Connection Explorers

PULSING AKR EMISSION DURING THE RECOVERY PHASE OF A LARGE STORM



δf/δt ~ -2.4 kHz/s

Ion speed~ 210 km/s

$\Delta\Phi_{//}$ ~ 1 kV

Pulsation at 2.8 Hz

Pottelette and Pickett, 2007

High time resolution measurements performed in the heart of the auroral acceleration region reveal:

♦ *Localized accelerating structures known as Double-Layers support « kV » field aligned potential drop,*

♦ *The DLs create strong assymetric turbulence leading to the generation of nonlinear structures: ion and electron holes,*

♦ *Both ion and electron hole dynamics may play a major role in the generation of the subtle fine AKR structures.*

Observational results encourage investigation of such radiating processes through numerical simulations: Astrophysical rdio sources?